1. Simulation evaluation of route-based control of bus operations

1. Chandrasekar, R; Cheu, RL; Chin, HC
2. JOURNAL OF TRANSPORTATION ENGINEERING
3. 2002

In this paper, results of an evaluation of an innovative strategy for minimizing bus bunching are presented. The strategy involves continuous monitoring of bus positions along their route and controlling bus spacing when necessary by employing signal priority and bus holding actions. The evaluation exercise aims to establish traffic and bus operating conditions when the strategy performs best. A simulation model of a hypothetical bus route developed using a PARAMICS (Parallel Microscopic Simulator) is used for this purpose. Bus bunching, measured in terms of disruptions to headways, is found to increase with decreases in design headway, increases in route length, and increases in traffic congestion. When bus spacing is controlled, a significant improvement is seen in cases of shorter design headways of 5 and 10 min, resulting in 80% of cases having more than 10% reduction in excess waiting time and 60% of the cases having more than 20% reduction in excess waiting time.

2. A headway-based approach to eliminate bus bunching: Systematic analysis and comparisons

1. Daganzo, Carlos F.
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2009

Bus schedules cannot be easily maintained on busy lines with short headways: experience shows that buses offering this type of service usually arrive irregularly at their stops, often in bunches. Although transit agencies build slack into their schedules to alleviate this problem - if necessary holding buses at control points to stay on schedule - their attempts often fail because practical amounts of slack cannot prevent large localized disruptions from spreading system-wide. This paper systematically analyzes an adaptive control scheme to mitigate this problem. The proposed scheme dynamically determines bus holding times at a route's control points based on real-time headway information. The method requires less slack than the conventional, schedule-based approach to produce headways within a given tolerance. This allows buses to travel faster than with the conventional approach, reducing in-vehicle passenger delay and increasing bus productivity. (C) 2009 Published by Elsevier Ltd.

3. Passengers' Perceptions and Effects of Bus-Holding Strategy using Automatic Vehicle Location Technology

1. Hanaoka, Shinya; Qadir, Fayyaz Mahmood
2. JOURNAL OF ADVANCED TRANSPORTATION
3. 2009

This study reports bus passengers' behavior and perceptions related to the use of potential features of an automatic vehicle location (AVL) system in bus transit through conducting an attitudinal on-board survey in Bangkok. A passenger waiting-time survey conducted as part of this study revealed that passengers perceive waiting-time at bus stops to be greater than actually experienced. The other aim of this study is to examine the potential benefits of bus-holding using an AVL technology, in terms of

> waiting-time, through minimizing bus bunching under different congestion levels. The results are obtained using PARAMICS, and reveal a significant reduction in average waiting-time.

4. A Bus-Following Model for Preventing Service Unreliability on a Circular Bus Route

1. Chen, Wei-Ya; Chen, Zhi-Ya
2. ICICTA: 2009 SECOND INTERNATIONAL CONFERENCE ON INTELLIGENT COMPUTATION TECHNOLOGY AND AUTOMATION, VOL III, PROCEEDINGS
3. 2009

> Aiming at decreasing average passenger waiting time at stops, headway adherence was used to measure the route-level transit service reliability for high frequency bus route services. Considering the fluctuation of passenger demand and the stochastic nature of running time on road segments, a bus-following model was built to prevent service unreliability on a circular route of high frequency bus services with recurrent buses. In the case study, the Monte-Carlo method was used to simulate the process of bus services. Headway variation and average passenger wait time at stops were statistically calculated for two different situations with no preventive control or preventive control. The results showed that, by pre-warning potential big headway deviation and triggering real-time preventive control strategies, bus bunching or big gap could be avoided and average passenger wait time at stops could be reduced.

5. Probability-based bus headway regularity measure

1. Lin, J. (J.); Ruan, M.
2. IET INTELLIGENT TRANSPORT SYSTEMS
3. 2009

> In frequently serviced bus routes passengers are more concerned about bus headway regularity than actual punctuality of bus arrival to the schedule. Buses arriving within very small (bus bunching) or very large headways are of particular concern and much less desirable. In this study, a time-point (stop) level probability-based headway regularity metric to measure bus service reliability is first formulated as a function of bus dwell time, number of stops into the trip, passenger activities (i.e. arrival, boarding and alighting) and expectation (or tolerance) of bus headways. The proposed metric is then applied to evaluate a Chicago Transit Authority bus route by using automatic vehicle location (AVL) data. It is found that headway regularity during a bus trip is closely impacted by dispatching headway. Furthermore, the time-point level service reliability declines as passenger activity levels increase or as the maximum passenger anticipated headway decreases (i.e. passengers become more demanding of frequent bus services). The case study demonstrates that the proposed probability-based headway regularity measure provides an operationable metric to transit agencies in terms of improving the transit service to meet passengers' expectation and thus increase ridership. Lastly, this study demonstrates another important application of the AVL/APC data.

6. Mesoscopic Modeling of Bus Public Transportation

1. Cats, Oded; Burghout, Wilco; Toledo, Tomer; Koutsopoulos, Hans N.
2. TRANSPORTATION RESEARCH RECORD
3. 2010

> Analysis of public transport system performance and level of service in urban areas is essential. Dynamic modeling of traffic conditions, passenger demand, and transit operations is important to represent adequately the complexity of and the interactions between these components in modern public transportation systems. This paper presents a transit simulation model designed to support evaluation of operations planning and control, especially in the context of advanced public transportation systems. Unlike most previous efforts in this area, the simulation model is built on a platform of a mesoscopic traffic simulation model, which allows modeling or the operation dynamics of large-scale transit systems, taking into account the main sources of service uncertainty and stochasticity. The capabilities of Mezzo as an evaluation tool of transit operations are demonstrated with an application to a real-world, high-demand bus line in metropolitan Tel Aviv, Israel, under various scenarios. The application shows that important phenomena such as bus bunching are reproduced realistically. A comparison of simulated running times and headway distributions with field data shows the model is capable of replicating observed data.

7. Reducing bunching with bus-to-bus cooperation

1. Daganzo, Carlos F.; Pilachowski, Josh
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2011

> Schedule-based or headway-based control schemes to reduce bus bunching are not resilient because they cannot prevent buses from losing ground to the buses they follow when disruptions increase the gaps separating them beyond a critical value. (Following buses are then overwhelmed with passengers and cannot process their work quick enough to catch up.) This critical gap problem can be avoided, however, if buses at the leading end of such gaps are given information to cooperate with the ones behind by slowing down. This paper builds on this idea. It proposes an adaptive control scheme that adjusts a bus cruising speed in real-time based on both, its front and rear spacings much as if successive bus pairs were connected by springs. The scheme is shown to yield regular headways with faster bus travel than existing control methods. Its simple and decentralized logic automatically compensates for traffic disruptions and inaccurate bus driver actions. Its hardware and data requirements are minimal.

8. Dynamic bus holding strategies for schedule reliability: Optimal linear control and performance analysis

1. Xuan, Yiguang; Argote, Juan; Daganzo, Carlos F.
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2011

> As is well known, bus systems are naturally unstable. Without control, buses on a single line tend to bunch, reducing their punctuality in meeting a schedule. Although conventional schedule-based strategies that hold buses at control points can alleviate this problem these methods require too much slack, which slows buses. This delays on-board passengers and increases operating costs. It is shown that dynamic holding strategies based on headways alone cannot help buses adhere to a schedule. Therefore, a family of dynamic holding strategies that use bus arrival deviations from a virtual schedule at the control points is proposed. The virtual schedule is introduced whether the system is run with a published schedule or not. It is shown that with this approach, buses can both closely adhere to a published schedule and maintain regular headways without too much slack. A one-parameter version

> of the method can be optimized in closed form. This simple method is shown to be near-optimal. To put it in practice, the only data needed in real time are the arrival times of the current bus and the preceding bus at the control point relative to the virtual schedule. The simple method was found to require about 40% less slack than the conventional schedule-based method. When used only to regulate headways it outperforms headway-based methods. (C) 2011 Elsevier Ltd. All rights reserved.

9. A self-coordinating bus route to resist bus bunching

1. Bartholdi, John J., III; Eisenstein, Donald D.
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2012

> The primary challenge for an urban bus system is to maintain constant headways between successive buses. Most bus systems try to achieve this by adherence to a schedule; but this is undermined by the tendency of headways to collapse, so that buses travel in bunches. To counter this, we propose a new method of coordinating buses. Our method abandons the idea of a schedule and even any a priori target headway. Under our scheme headways are dynamically self-equalizing and the natural headway of the system tends to emerge spontaneously. Headways also become self-correcting in that after disturbances they reequalize without intervention by management or even awareness of the drivers. We report on a successful implementation to control a bus route in Atlanta. (C) 2011 Elsevier Ltd. All rights reserved.

10. Synchronization of bus timetabling

1. Ibarra-Rojas, Omar J.; Rios-Solis, Yasmin A.
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2012

> Timetable generation is a subproblem of bus network strategic planning, in which the departure time of each trip is determined. We study the bus network of Monterrey, Mexico, which is similar to those of other cities in Latin America. It is a large bus network where passenger transfers must be favored, almost evenly spaced departures are sought, and bus bunching of different lines must be avoided. We formulate the timetabling problem of this network with the objective of maximizing the number of synchronizations to facilitate passenger transfers and avoid bus bunching along the network. We define these synchronizations as the arrivals of two trips with a separation time within a time window to make a flexible formulation. This flexibility is a critical aspect for the bus network, since travel times vary because of reasons such as driver speed, traffic congestion, and accidents. By proving that our problem is NP-hard we answer a 10-year-old open question about the NP-hardness of similar problems present in literature. Next, we analyze the structural properties of the feasible solution space of our model. This analysis leads to a preprocessing stage that eliminates numerous decision variables and constraints. Moreover, this preprocessing defines feasible synchronization and arrival time windows that are used in a new metaheuristic algorithm. Empirical experimentation shows that our proposed algorithm obtains high-quality solutions for real-size instances in less than one minute. (C) 2012 Elsevier Ltd. All rights reserved.

11. How much can holding and/or limiting boarding improve transit performance?

1. Delgado, Felipe; Carlos Munoz, Juan; Giesen, Ricardo
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL

3. 2012

> Bus bunching affects transit operations by increasing passenger waiting times and its variability. This work proposes a new mathematical programming model to control vehicles operating on a transit corridor minimizing total delays. The model can handle a heterogeneous fleet of vehicles with different capacities without using binary variables, which make solution times compatible with real-time requirements. Two control policies are studied within a rolling horizon framework: (i) vehicle holding (HRT), which can be applied at any stop and (ii) holding combined with boarding limits (HBLRT), in which the number of boarding passengers at any stop can be limited in order to increase operational speed. Both strategies are evaluated in a simulation environment under different operational conditions. The results show that HBLRT and HRT outperform other benchmark control strategies in all scenarios, with savings of excess waiting time of up to 77% and very low variability in performance. HBLRT shows significant benefits in relation to HRT only under short headway operation and high passenger demand. Moreover, our results suggest implementing boarding limits only when the next arriving vehicle is nearby. Interestingly, in these cases HBLRT not only reduces an extra 6.3% the expected waiting time in comparison with HRT, but also outperforms other control schemes in terms of comfort and reliability to both passengers and operators. To passengers HBLRT provide a more balanced load factor across vehicles yielding a more comfortable experience. To operators the use of boarding limits speed up vehicles reducing the average cycle time and its variability, which is key for a smooth operation at terminals.

12. An Improved Model for Headway-Based Bus Service Unreliability Prevention with Vehicle Load Capacity Constraint at Bus Stops

1. Chen, Weiya; Yang, Chunhua; Feng, Fenling; Chen, Zhiya
2. DISCRETE DYNAMICS IN NATURE AND SOCIETY
3. 2012

> This paper presents an improved model for improving headway-based bus route service reliability at bus stops using real-time preventive operation control, taking into account dynamic interaction among random passenger demand, stochastic driving conditions of route segments, and vehicle load capacity constraint. In this model, the real-time information of passenger demand and vehicle operation is involved to predict the imminent unacceptable headway deviation, in the case of which some in-time preventive control strategies are deployed according to the given control rules. As a case study, a single fixed bus route with high-frequency services was simulated and different scenarios of real-time preventive operation control were performed. Headway adherence and average passenger wait time were used to measure bus service reliability. The results show that the improved model is closer to the real bus route service, and using real-time information to predict potential service unreliability and trigger in-time preventive control can reduce bus bunching and avoid big gap.

13. Potential of Low-Frequency Automated Vehicle Location Data for Monitoring and Control of Bus Performance

1. Yang, Yingxiang; Gerstle, David; Widhalm, Peter; Bauer, Dietmar; Gonzalez, Marta
2. TRANSPORTATION RESEARCH RECORD
3. 2013

> The potential of low-frequency bus localization data for the monitoring and control of bus system performance is investigated in this paper. It is shown that data with a sampling rate as low as 1 min, when processed appropriately, can provide ample information. Accurate estimates of stop arrival and departure times are obtained; these estimates in turn allow the analysis of headways and travel times. A three-parameter gamma family of distributions is fitted for headways at the stops along a bus line. The evolution of the parameters demonstrates critical points on the line where bus bunching is significantly increased. Moreover, this analysis allows differentiating problems associated with varying passenger demand from uncertainties associated with traffic conditions. Furthermore it is shown that expected travel time and travel time variability can be calculated from low-frequency localization data. Finally, the way in which the results can be used to calibrate a simulation model that can test bus control strategies is presented. The methods are applied and validated to data obtained from Bus Route Number 1 in Boston, Massachusetts.

14. Comparison of dynamic control strategies for transit operations

1. Carlos Munoz, Juan; Cortes, Cristian E.; Giesen, Ricardo; Saez, Doris; Delgado, Felipe; Valencia, Francisco; Cipriano, Aldo
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2013

> Real-time headway-based control is a key issue to reduce bus bunching in high frequency urban bus services where schedules are difficult to implement. Several mechanisms have been proposed in the literature, but very few performance comparisons are available. In this paper two different approaches are tested over eight different scenarios. Both methodologies solve the same problem, the former based on a deterministic optimization over a long-term rolling horizon, while the latter proposes a hybrid predictive approach considering a shorter horizon and a stochastic evolution of the system. The comparison is conducted through scenarios that include three different dimensions: (i) bus capacities which can be reached or not, (ii) service frequencies, considering high and medium frequency services and (iii) different load profiles along the corridor. The results show that the deterministic approach performs better under scenarios where bus capacity could be reached frequently along the route while the hybrid predictive control approach performs better in situations where this does not happen.

15. Implementation of an iterative headway-based bus holding strategy with real-time information

1. Chen, Qin; Adida, Elodie; Lin, Jane
2. PUBLIC TRANSPORT
3. 2013

> In high frequency bus service lines buses often come irregularly at the stops, often in bunches, due to the uncertainty of the passenger demand and behavior and unexpected conditions on the roads. Vehicle holding is a commonly used strategy among a variety of control strategies in transit operation in order to reduce bus bunching and regulate bus headways. This paper investigates a control strategy of holding a group of buses at a single or multiple control point(s). By incorporating any passenger boarding activities during holding, a single control point problem is developed and extended to multiple control points to reduce the variance of headways for the downstream stops. The problem is a non-convex optimization problem with linear constraints that minimizes the total passenger waiting

> time both on-board and at stops. A heuristic is then developed that is easy and fast to implement, which makes it suitable for real-time implementation. The model is evaluated with a simulation case study by using the real-time bus operation data (i.e., Automatic Vehicle Location and Automatic Passenger Count Data) from the Chicago Transit Authority (CTA). The simulation results show that considering the boarding activities in the total waiting time, our model mitigates the error propagation and maintains steady performance, compared to the common models in the literature, which do not consider boarding while holding.

16. An Incremental Probabilistic Model to Predict Bus Bunching in Real-Time

1. Moreira-Matias, Luis; Gama, Joao; Mendes-Moreira, Joao; de Sousa, Jorge Freire
2. ADVANCES IN INTELLIGENT DATA ANALYSIS XIII
3. 2014

> In this paper, we presented a probabilistic framework to predict Bus Bunching (BB) occurrences in real-time. It uses both historical and real-time data to approximate the headway distributions on the further stops of a given route by employing both offline and online supervised learning techniques. Such approximations are incrementally calculated by reusing the latest prediction residuals to update the further ones. These update rules extend the Perceptron's delta rule by assuming an adaptive beta value based on the current context. These distributions are then used to compute the likelihood of forming a bus platoon on a further stop - which may trigger an threshold-based BB alarm. This framework was evaluated using real-world data about the trips of 3 bus lines throughout an year running on the city of Porto, Portugal. The results are promising.

17. Bus control strategy application: case study of Santiago transit system

1. Lizana, Pedro; Carlos Munoz, Juan; Giesen, Ricardo; Delgado, Felipe
2. 5TH INTERNATIONAL CONFERENCE ON AMBIENT SYSTEMS, NETWORKS AND TECHNOLOGIES (ANT-2014), THE 4TH INTERNATIONAL CONFERENCE ON SUSTAINABLE ENERGY INFORMATION TECHNOLOGY (SEIT-2014)
3. 2014

> Buses have an inherent tendency to bunch due to randomness in passenger demand and congestion. Many sophisticated control strategies have been developed to reduce bus bunching, however, few of them have been implemented in high frequency real services. Building upon a control strategy comprised of a rolling horizon mathematical programming model that yields the optimal holding time that minimizes user-waiting times(6), we have developed real-time software and implemented it on two bus services in Santiago using different technologies to communicate the instructions to bus drivers. The results presented in this paper are encouraging, on the days the system was implemented less bus bunching was observed, which translated in fewer headway-irregularity fines. Moreover lower passenger fare evasion was observed when the bus control strategy was used. (C) 2014 Published by Elsevier B.V.

18. Regularity-driven bus operation: Principles, implementation and business models

1. Cats, Oded
2. TRANSPORT POLICY
3. 2014

> Service reliability is a key determinant of public transport performance. In the context of high-frequency urban lines, irregular service results with long waiting times, bunched vehicles, long delays, uneven passenger loads, poor capacity utilization and higher operational costs. Field experiments were conducted in Stockholm, Sweden, in order to test the feasibility and implications of a regularity-driven operation scheme designed to mitigate bus bunching and facilitated by a real-time control strategy. This paper investigates alternative service indicators and business models that could best support the long-term implementation of operation geared towards better regularity performance. A paradigm shift towards regularity-based service evidently requires the consideration of a series of measures along the service chain as it involves a paradigm shift in production planning, operations, control center and performance monitoring.

19. Sequential Framework for Short-Term Passenger Flow Prediction at Bus Stop

1. Gong, Min; Fei, Xiang; Wang, Zhi Hu; Qiu, Yun Jie
2. TRANSPORTATION RESEARCH RECORD
3. 2014

> Short-term prediction of passenger flow plays an important role in real-time bus dispatching. Such prediction is also useful in diagnosing bus operation problems, such as forecasting bus bunching. A novel framework is proposed in this paper to predict the passenger flow at bus stops. The framework consists of three sequential stages. In the first stage, a seasonal ARIMA-based method is used to predict the arrival passenger count and empty space on a bus when the bus reaches a bus stop. The historical passenger arrivals at the bus stop can be obtained from the corresponding boarding count data by an allocation approach. In the second stage, an event-based method is developed to predict the departure passenger counts from the stop. The proposed method iteratively forecasts the bus arrival events and consequently updates the passenger flow. In the third stage, a Kalman filter based method is proposed to predict the waiting passenger counts at the stop according to results from the first and second stages. The real-time observed waiting passenger count is used as the feedback of the filter to minimize the prediction error. Computational results based on the real bus line data for passenger flow prediction and its application in forecasting bunching confirm that the proposed framework and solution algorithm are effective in providing accurate and reliable passenger flow prediction.

20. A model of bus bunching under reliability-based passenger arrival patterns

1. Fonzone, Achille; Schmocker, Jan-Dirk; Liu, Ronghui
2. 21ST INTERNATIONAL SYMPOSIUM ON TRANSPORTATION AND TRAFFIC THEORY
3. 2015

> If bus service departure times are not completely unknown to the passengers, non-uniform passenger arrival patterns can be expected. We propose that passengers decide their arrival time at stops based on a continuous logit model that considers the risk of missing services. Expected passenger waiting times are derived in a bus system that allows also for overtaking between bus services. We then propose an algorithm to derive the dwell time of subsequent buses serving a stop in order to illustrate when bus bunching might occur. We show that non-uniform arrival patterns can significantly influence the bus bunching process. With case studies we find that, even without exogenous delay, bunching can arise when the boarding rate is insufficient given the level of overall demand. Further, in case of exogenous delay, non-uniform arrivals can either worsen or improve the bunching conditions,

> depending on the level of delay. We conclude that therefore such effects should be considered when service control measures are discussed. (C) 2015 The Authors. Published by Elsevier B.V.

21. A model of bus bunching under reliability-based passenger arrival patterns

1. Fonzone, Achille; Schmoecker, Jan-Dirk; Liu, Ronghui
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2015

> If bus service departure times are not completely unknown to the passengers, non-uniform passenger arrival patterns can be expected. We propose that passengers decide their arrival time at stops based on a continuous logit model that considers the risk of missing services. Expected passenger waiting times are derived in a bus system that allows also for overtaking between bus services. We then propose an algorithm to derive the dwell time of subsequent buses serving a stop in order to illustrate when bus bunching might occur. We show that non-uniform arrival patterns can significantly influence the bus bunching process. With case studies we find that, even without exogenous delay, bunching can arise when the boarding rate is insufficient given the level of overall demand. Further, in case of exogenous delay, non-uniform arrivals can either worsen or improve the bunching conditions, depending on the level of delay. We conclude that therefore such effects should be considered when service control measures are discussed. (C) 2015 Elsevier Ltd. All rights reserved.

22. Finding Causes of Irregular Headways Integrating Data Mining and AHP

1. An, Shi; Zhang, Xinming; Wang, Jian
2. ISPRS INTERNATIONAL JOURNAL OF GEO-INFORMATION
3. 2015

> Irregular headways could reduce the public transit service level heavily. Finding out the exact causes of irregular headways will greatly help to develop efficient strategies aiming to improve transit service quality. This paper utilizes bus GPS data of Harbin to evaluate the headway performance and proposes a statistical method to identify the abnormal headways. Association mining is used to dig deeper and recognize six causes of bus bunching. The AHP, embedded data analysis, is applied to determine the weight of each cause in the case of that these causes are combined with each other constantly. Results show that the front bus has a greater effect on bus bunching than the following bus, and the traffic condition is the most critical factor affecting bus headway.

23. Analysis of real-time control strategies in a corridor with multiple bus services

1. Hernandez, Daniel; Carlos Munoz, Juan; Giesen, Ricardo; Delgado, Felipe
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2015

> Control strategies have been widely used in the literature to counteract the effects of bus bunching in passenger's waiting times and its variability. These strategies have only been studied for the case of a single bus line in a corridor. However, in many real cases this assumption does not hold. Indeed, there are many transit corridors with multiple bus lines interacting, and this interaction affects the efficiency of the implemented control mechanism. This work develops an optimization model capable of executing a control scheme based on holding strategy for a corridor with multiple bus lines. We analyzed the benefits in the level of service of the public transport system when considering a central

> operator who wants to maximize the level of service for users of all the bus lines, versus scenarios where each bus line operates independently. A simulation was carried out considering two medium frequency bus lines that serve a set of stops and where these two bus lines coexist in a given subset of stops. In the simulation we compared the existence of a central operator, using the optimization model we developed, against the independent operation of each line. In the simulations the central operator showed a greater reduction in the overall waiting time of the passengers of 55% compared to a no control scenario. It also provided a balanced load of the buses along the corridor, and a lower variability of the bus headways in the subset of stops where the lines coexist, thus obtaining better reliability for all types of passengers present in the public transport system.

24. Improving Bus Service Reliability with Stochastic Optimization

1. Gkiotsalitis, Konstantinos; Maslekar, Nitin
2. 2015 IEEE 18TH INTERNATIONAL CONFERENCE ON INTELLIGENT TRANSPORTATION SYSTEMS
3. 2015

> Bus route performance, typically expressed in terms of excess waiting time (EWT), is often unstable and suffers from bunching which results in lower regularity. Governments are introducing regularity-based contracts for operators, where monetary incentives or penalties are introduced depending on performance. Optimization of bus regularity requires the recursive coordination of several buses, hindering the solution scalability in real-time. In this work we propose a bus headway balancer based on stochastic search and branch hopping/merging algorithm which optimizes schedules to minimize the EWT. This algorithm balances bus headway deviations by introducing dwell intervals in the schedule, which can be applied off line or in real-time. A test-case implementation of the approach used 3-month AVL data from a bus operator in Asia and showcased an improvement of EWT by up to 50% with reduction in computational complexity to almost linear time and at least 2x times increase at solution space search.

25. Dynamic control of complex transit systems

1. Argote-Cabanero, Juan; Daganzo, Carlos F.; Lynn, Jacob W.
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2015

> This paper proposes a dynamic control method to overcome bunching and improve the regularity of fixed-route transit systems. The method uses a combination of dynamic holding and en-route driver guidance to achieve its objectives. It applies to systems with a mix of headway-based and schedule-based lines but it is evaluated for scheduled systems as this is the more challenging application. Improved schedule adherence is the goal. The method's calculation complexity per piece of advice does not increase with system size. As a result, the method is scalable and can be used with large multi-line systems, no matter how complex. When controlled, each vehicle is mostly affected by exogenous disturbances (e.g. traffic) and very little by other vehicles. As a result, disruptions to a vehicle or group of vehicles caused by inattentive drivers or control equipment failures remain confined to the vehicles experiencing the problems. The control method effectively quarantines disease. The method is evaluated analytically and with simulations over a broad range of conditions, including schedules with zero slack. The method was also evaluated by observing the performance of a real world multi-line system that uses inexpensive on-board tablets to apply the control. The evaluation

> addresses driver compliance and equipment malfunction issues. It is found that the method is resilient and improves reliability considerably even under challenging conditions. (C) 2015 Elsevier Ltd. All rights reserved.

26. Distributed Automatic Vehicle Location (AVL) System Based on Connected Vehicle Technology

1. Smietanka, Piotr; Szczypiorski, Krzysztof; Viti, Francesco; Seredynski, Marcin
2. 2015 IEEE 18TH INTERNATIONAL CONFERENCE ON INTELLIGENT TRANSPORTATION SYSTEMS
3. 2015

> The efficiency of Public Transport (PT) has significantly improved thanks to Automatic Vehicle Location (AVL) systems. They are used by several applications, such as real-ime passenger information systems, transit signal priority, and control schemes designed to reduce the negative effects of bus bunching. Currently, these applications rely on a centralised architecture, i.e. buses equipped with communication and location detection technologies constantly send their positions to the AVL centre. In this paper, we demonstrate how a distributed AVL system can be designed on the basis of Connected Vehicle (CV) technology, i.e. information about bus location is exchanged in the PT network via buses equipped with the technology. Using computation experiments based on microscopic traffic simulations we demonstrate that CV-based AVL works efficiently when it comes to providing a bus with information about locations of buses ahead of it. However, information about buses behind is far less reliable, and requires additional support in message dissemination (e.g. by private vehicles).

27. A real-time bus dispatching policy to minimize passenger wait on a high frequency route

1. Berrebi, Simon J.; Watkins, Kari E.; Laval, Jorge A.
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2015

> One of the greatest problems facing transit agencies that operate high-frequency routes is maintaining stable headways and avoiding bus bunching. In this work, a real-time holding mechanism is proposed to dispatch buses on a loop-shaped route using real-time information. Holds are applied at one or several control points to minimize passenger waiting time while maintaining the highest possible frequency, i.e. using no buffer time. The bus dispatching problem is formulated as a stochastic decision process. The optimality equations are derived and the optimal holding policy is found by backward induction. A control method that requires much less information and that closely approximates the optimal dispatching policy is found. A simulation assuming stochastic operating conditions and unstable headway dynamics is performed to assess the expected average waiting time of passengers at stations. The proposed control strategy is found to provide lower passenger waiting time and better resiliency than methods used in practice and recommended in the literature. Published by Elsevier Ltd.

28. Integrated Real-Time Transit Signal Priority Control for High-Frequency Segregated Transit Services

1. Delgado, Felipe; Carlos Munoz, Juan; Giesen, Ricardo; Wilson, Nigel H. M.
2. TRANSPORTATION RESEARCH RECORD
3. 2015

> Bus bunching affects transit operations by increasing passenger waiting time and variability. To tackle this phenomenon, a wide range of control strategies has been proposed. However, none of them have considered station and interstation control together. In this study station and interstation control were tackled to determine the optimal vehicle control strategy for various stops and traffic lights in a single service transit corridor. The strategy minimized the total time that users must devote to making a trip, taking into account delays for transit and general traffic users. Based on a high-frequency, capacity-constrained, and unscheduled service (no timetable) for which real-time information about bus position (GPS) and bus load (automated passenger counter) is available, this study focused on strategies for traffic signal priority in the form of green extension considered together with holding buses at stops and limiting passenger boarding at stops. The decisions on transit signal priority were made according to a rolling horizon scheme in which effects over the whole corridor were considered in every single decision. The proposed strategy was evaluated in a simulated environment under different operational conditions. Results showed that the proposed control strategy achieves reductions in the excess delay for transit users close to 61.4% compared with no control, while general traffic increases only by 1.5%.

29. Quantifying the effects of driver non-compliance and communication system failure in the performance of real-time bus control strategies

1. Phillips, William; del Rio, Andres; Carlos Munoz, Juan; Delgado, Felipe; Giesen, Ricardo
2. TRANSPORTATION RESEARCH PART A-POLICY AND PRACTICE
3. 2015

> Control strategies that prevent bus bunching allow for improvement to the level of service offered by a transit corridor as well as reducing travel time and its variability, thus providing higher reliability to the user. Several optimization models based on the use of real-time information have been shown to achieve this, through the planning of holding of the buses at bus stops. In the majority of the cases the benefits of these models have been estimated assuming ideal operational conditions while only few of them have been tested in real conditions. However, neither the simulation experiment, nor the real implementations have quantified the effects of real-life phenomena that harm the performance of the system, preventing it from achieving the full potential of these control schemes. This paper examines three phenomena that may occur during the operation of a bus service, which would limit the effectiveness of a holding-based control strategy in the sense that some of the planned holdings might not be executed. These phenomena are drivers non-compliance, failure of communication systems with buses, and the combination of both. The objective is to estimate the negative impact these phenomena can have on the benefits of the strategy, and to identify possible measures that could help operators and decision makers to reduce this impact. Both objectives are achieved using the real-time holding model developed by Delgado et al. (2012), which is tested in a simulation environment.

30. Real-time bus route state forecasting using particle filter and mesoscopic modeling

1. Hans, Etienne; Chiabaut, Nicolas; Leclercq, Ludovic; Bertini, Robert L.
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2015

> In the absence of system control strategies, it is common to observe bus bunching in transit operations. A transit operator would benefit from an accurate forecast of bus operations in order to

> control the system before it becomes too disrupted to be restored to a stable condition. To accomplish this, we present a general bus prediction framework. This framework relies on a stochastic and event-based bus operation model that provides sets of possible bus trajectories based on the observation of current bus positions, available via global positioning system (GPS) data. The median of the set of possible trajectories, called a particle, is used as the prediction. In particular, this enables the anticipation of irregularities between buses. Several bus models are proposed depending on the dwell and inter-stop running time representations. These models are calibrated and applied to a real case study thanks to the high quality data provided by TriMet (the Portland, Oregon, USA transit district). Predictions are finally evaluated by an a posteriori comparison with the real trajectories. The results highlight that only bus models accounting for the bus load can provide valid forecasts of a bus route over a large prediction horizon, especially for headway variations. Accounting for traffic signal timings and actual traffic flows does not significantly improves the prediction. Such a framework paves the way for further development of refined dynamic control strategies for bus operations.

31. Mitigating Bunching with Bus-following Models and Bus-to-bus Cooperation

1. Ampountolas, Konstantinos; Kring, Malcolm
2. 2015 IEEE 18TH INTERNATIONAL CONFERENCE ON INTELLIGENT TRANSPORTATION SYSTEMS
3. 2015

> Bus bunching is an instability problem where buses operating on high frequency public transport lines arrive at stops in bunches. In this work, we unveil that bus-following models can be used to design bus-to-bus cooperative control strategies and mitigate bunching. The use of bus-following models avoids the explicit modelling of bus-stops, which would render the resulting problem discrete, with events occurring at arbitrary time intervals. In a follow-the-leader two-bus system, bus-to-bus communication allows the driver of the following bus to observe (from a remote distance) the position and speed of a lead bus operating in the same transport line. The information transmitted from the lead bus is then used to control the speed of the follower to eliminate bunching. In this context, we first propose practical linear and nonlinear control laws to regulate space headways and speeds, which would lead to bunching cure. Then a combined state estimation and remote control scheme, which is based on the Linear-Quadratic Gaussian theory, is developed to capture the effect of bus stops, traffic disturbances, and randomness in passenger arrivals. To investigate the behaviour and performance of the developed approaches the 9-km 1-California line in San Francisco with about 50 arbitrary spaced bus stops is used. Simulations with real passenger data obtained from the San Francisco Municipal Transportation Agency are carried out. Results show bunching avoidance and significant improvements in terms of schedule reliability of bus services and delays. The proposed control is robust, scalable in terms of public transport network size, and thus easy to implement in real-world settings.

32. Real-time bus route state forecasting using Particle Filter: An empirical data application

1. Hans, Etienne; Chiabaut, Nicolas; Leclercq, Ludovic; Bertini, Robert L.
2. 4TH INTERNATIONAL SYMPOSIUM OF TRANSPORT SIMULATION (ISTS'14) SELECTED PROCEEDINGS
3. 2015

> Buses on the same route tend to bunch when the system is uncontrolled. This lack of regularity leads to an increase in the average passenger waiting time, increases delays and makes travel times uncertain. A wide variety of solutions have been proposed to maintain accurate bus system

> performance. Unfortunately, if a strategy is applied permanently, it could detract from the entire transport system efficiency. That is why a transit operator needs an accurate forecast of the route in order to intervene before the bus route is too disrupted to be restored to regularity. This paper aims to predict critical situations in real-time forecasting of a bus route state. To accomplish this, we propose to take advantage of both theoretical and empirical information (model and data) using data assimilation (a particle filter). On one hand, a stochastic dynamic bus model forecasts future bus route states. On the other hand, archived data calibrates the model parameters while real-time data provides information about the actual route state. The methodology is applied to a real case study thanks to the quality data provided by TriMet (the Portland, Oregon transit district). Predictions are finally evaluated by an a posteriori comparison with real data. The results highlight that the method leads to a valid forecast of a bus route state with a 8 minutes time window. This duration is sufficient to predict critical situations, especially bus bunching. Further research would have to consider deterministic travel times from a traffic model instead of the distributions in order to maintain correlation between travel times on links. In that case, the assimilation process would focus on the surrounding traffic flow, also potentially available in the Portland data. (C) 2015 The Authors. Published by Elsevier B.V.

33. Locating fixed roadside units in a bus transport network for maximum communications probability

1. Rios, Miguel; Marianov, Vladimir; Perez, Melisa
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2015

> A key issue in solving the difficult bus-bunching problem' is being able to have reliable information about the location of the buses in the network. Most advanced public transport systems have buses with GPS devices, but the problem remains of how to send reliable information from the buses to the control unit, particularly when the density of buses is low, but there are high communications reliability requirements. As a solution, we study locating roadside units (RSUs) along the route. The buses, together with the RSUs, form a linear vehicular ad-hoc network (VANET). The RSUs are deployed so to maximize the probability of a vehicle communicating with an RSU in at most two hops. Previous studies on RSU location never took into account two hops, a conceptually different type of network. Rather, they consider that a vehicle is able to communicate only directly to an RSU (one hop), which is a well-known Maximum Covering Problem, in which one of the parties is always immobile, similar to a mobile phone network. Oppositely, our method solves the problem in which two of the intervening parties are mobile and communicate with each other, not possible to solve as a Maximum Covering Problem. We estimate the probability of a vehicle accessing successfully an RSU either directly or through the relay of another vehicle. This probability is later embedded in an integer programming formulation that optimizes the RSU locations for maximum communications likelihood. Numerical examples show that the connection probability is strongly dependent on the coverage ratio of the transmitters and receivers and relatively independent on the vehicle density on the network, when densities are low. Results also show that it is possible to find some cost-efficient solutions which result in a smaller number of RSUs located while assuring a connection probability of 0.9 or higher. (C) 2015 Elsevier Ltd. All rights reserved.

34. Headway-based bus bunching prediction using transit smart card data

1. Yu, Haiyang; Chen, Dongwei; Wu, Zhihai; Ma, Xiaolei; Wang, Yunpeng
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES

3. 2016

> Bus bunching severely deteriorates the quality of transit service with poor on-time performance and excessive waiting time. To mitigate bus bunching, this paper presents a predictive framework to capture the stop-level headway irregularity based on transit smart card data. Historical headway, passenger demands, and travel time are utilized to model the headway fluctuation at the following stops. A Least Squares Support Vector Machine regression is established to detect bus bunching with the predicted headway pattern. An empirical experiment with two bus routes in Beijing is conducted to demonstrate the effectiveness of the proposed approach. The predictive method can successfully identify more than 95% of bus bunching occurrences in comparison with other well-established prediction algorithms. Moreover, the detection accuracy does not significantly deteriorate as the prediction lead time increases. Instead of regularizing the headways at all costs by adopting certain correction actions, the proposed framework can provide timely and accurate information for potential bus bunching prevention and inform passengers when the next bus will arrive. This feature will greatly increase transit ridership and reduce operating costs for transit authorities.

35. Bus bunching along a corridor served by two lines

1. Schmocker, Jan-Dirk; Sun, Wenzhe; Fonzone, Achille; Liu, Ronghui
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2016

> Headway fluctuations and bus bunching are well known phenomena on many bus routes where an initial delay to one service can disturb the whole schedule due to resulting differences in dwell times of subsequent buses at stops. This paper deals with the influence of a frequent but so far largely neglected characteristic of bus networks on bus bunching, that is the presence of overtaking and common lines. A set of discrete state equations is implemented to obtain the departure times of a group of buses following the occurrence of an exogenous delay to one bus at a bus stop. Two models are distinguished depending on whether overtaking at stops is possible or not. If two buses board simultaneously and overtaking is not possible, passengers will board the front bus. If overtaking is possible, passengers form equilibrium queues in order to minimise their waiting times. Conditions for equilibrium queues among passengers with different choice sets are formulated. With a case study we then illustrate that, if overtaking is not allowed, the presence of common lines worsens the service regularity along the corridor. Conversely, common lines have positive effects when overtaking is possible. We suggest hence that appropriate network design is important to reduce the negative effects of delay-prone lines on the overall network performance.

36. An online learning approach to eliminate Bus Bunching in real-time

1. Moreira-Matias, Luis; Cats, Oded; Gama, Joao; Mendes-Moreira, Joao; de Sousa, Jorge Freire
2. APPLIED SOFT COMPUTING
3. 2016

> Recent advances in telecommunications created new opportunities for monitoring public transport operations in real-time. This paper presents an automatic control framework to mitigate the Bus Bunching phenomenon in real-time. The framework depicts a powerful combination of distinct

> Machine Learning principles and methods to extract valuable information from raw location-based data. State-of-the-art tools and methodologies such as Regression Analysis, Probabilistic Reasoning and Perceptron's learning with Stochastic Gradient Descent constitute building blocks of this predictive methodology. The prediction's output is then used to select and deploy a corrective action to automatically prevent Bus Bunching. The performance of the proposed method is evaluated using data collected from 18 bus routes in Porto, Portugal over a period of one year. Simulation results demonstrate that the proposed method can potentially reduce bunching by 68% and decrease average passenger waiting times by 4.5%, without prolonging in-vehicle times. The proposed system could be embedded in a decision support system to improve control room operations. (C) 2016 Published by Elsevier B.V.

37. A Self-Adjusting Method to Resist Bus Bunching Based on Boarding Limits

1. Zhao, Shuzhi; Lu, Chunxiu; Liang, Shidong; Liu, Huasheng
2. MATHEMATICAL PROBLEMS IN ENGINEERING
3. 2016

> Bus bunching is one of the most serious problems of urban bus systems. Bus bunching increases waiting and travel time of passengers. Many bus systems use schedules to reach equal headways. Compared to the idea of schedules and the target headway introduced later, we propose a new method to improve the efficiency of a bus system and avoid bus bunching by boarding limits. Our solution can be effectively implemented when buses cannot travel as planned because of bad road conditions and dynamic demands at bus stops. Besides, using our method, bus headways reach the state with equal headways dynamically and spontaneously without drivers' explicit intervention. Moreover, the method can improve the level of the bus service and reduce total travel time of passengers. We verify our method using an ideal bus route and a real bus route, both showing the success of the proposed method.

38. Holding Control of Bus Bunching without Explicit Service Headways

1. Zimmermann, Lucas; Kraus, Werner, Jr.; Koehler, Luiz Alberto; Camponogara, Eduardo
2. IFAC PAPERSONLINE
3. 2016

> Holding-based control methods for bus operation are examined to point out that allowing greater variance in headways between consecutive buses leads to possible gains in total delay, as compared to strict adherence to a service headway. This result, obtained empirically, indicates that optimal operation is not necessarily attained with even headways. Such finding is related to the well-known fact that there should not be too many control points for headway corrections when operating under the traditional method of scheduled departures from bus stations. Current feedback and predictive methods, however, can be productively applied at all stations, hence the importance of studying the effects of frequent control actions. Several feedback schemes are tested, as well as a rolling horizon predictive control method that seeks to minimize onboard and at, station delays. The latter has 110 headway reference and hence yields larger headway variations. The scenario is a BET corridor modeled in a microsimulation environment,. Simulation results indicate gains of 29% in total delay for predictive control in relation to open loop operation, and superior performance when compared to the tested proportional feedback control methods. (C) 2016, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.

39. Have they bunched yet? An exploratory study of the impacts of bus bunching on dwell and running times

1. Verbich, David; Diab, Ehab; El-Geneidy, Ahmed
2. PUBLIC TRANSPORT
3. 2016

> If transit agencies wish to retain and attract riders, they need to provide reliable and efficient services. Transit agencies tend to run high-frequency bus routes during peak hours, and in many cities, different routes can also overlap along major corridors. In some instances, consecutive buses can arrive at a shared stop simultaneously or one bus may arrive while another bus is currently servicing the stop. This phenomenon, known as bus bunching, can delay buses and passengers, and is usually inefficient. In this study, we attempt to understand how bus bunching from the same or different routes can impact bus operations, specifically dwell and running times. This research uses stop-level records obtained from automatic vehicle location (AVL) and automatic passenger counter (APC) systems from TriMet, Portland, OR. Using linear modeling, we find that bus bunching increases both dwell and running times. Specifically, when different routes bunch or are scheduled to arrive at a bus stop within a short time frame, or when buses from the same route arrive with a short time frame, dwell times increase by similar to 10 s. Similarly, bus bunching from the same route or different route prolongs running times by similar to 40 s. Our findings suggest that bus schedulers and operators should consider adding more time between consecutive buses from different routes at shared stops to minimize the negative impacts that we observed from bus bunching.

40. Real-Time Public-Transport Operational Tactics Using Synchronized Transfers to Eliminate Vehicle Bunching

1. Nesheli, Mahmood Mahmoodi; Ceder, Avishai; Gonzalez, Vicente A.
2. IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS
3. 2016

> Scheduled public transport (PT) service on a defined network often encounters unforeseen variations of arrival times mainly because of traffic problems, unexpected passenger demand, and driver behavior. These variations will create the undesirable vehicle (particularly bus) bunching phenomenon unless a proper control action is introduced. This study develops a methodology to attain optimally real-time control actions to minimize the bunching phenomenon. To this end, a library of selected operational tactics is constructed, for the PT operators, not only to assist in reducing vehicle bunching but also to increase the likelihood of direct (without await) transfers. The library of operational tactics serves as a basis for a process of real-time control actions to maintain the scheduled headway and thus achieving maximal transfer synchronization. The methodology developed, using simulation, is applied to a case study of actual bus routes operated in the region of Auckland, New Zealand. The results imply what tactic to use in real time, what is the optimal control strength, and what is the saving of riding and waiting times in comparison with PT operation without using tactics. The findings show that a significant improvement, in avoiding bunching and increasing the number of direct transfers, is attained by the use of a combination of selected tactics.

41. Bus control strategies in corridors with signalized intersections

1. Estrada, Miquel; Mension, Josep; Aymami, Josep M.; Torres, Laura

2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2016

> This paper proposes a new dynamic bus control strategy aimed at reducing the negative effects of time-headway variations on route performance, based on real-time bus tracking data at stops. In routes with high demand, any delay of a single vehicle ends up causing an unstable motion of buses and producing the bus bunching phenomena. This strategy controls the cruising speed of buses and considers the extension of the green phase of traffic lights at intersections, when a bus is significantly delayed. The performance of this strategy will be compared to the current static operation technique based on the provision of slack times at holding points. An operational model is presented in order to estimate the effects of each controlling strategy, taking into account the vehicle capacity constraint. Control strategies are assessed in terms of passenger total travel time, operating cost as well as on the coefficient of headway variation. The effects of controlling strategies are tested in an idealized bus route under different operational settings and in the bus route of highest demand in Barcelona by simulation. The results show that the proposed dynamic controlling strategy reduces total system cost (user and agency) by 15-40% as well as the coefficient of headway variation 53-78% regarding the uncontrolled case, providing a bus performance similar to the expected when time disturbance is not presented.

42. A self-adaptive method to equalize headways: Numerical analysis and comparison

1. Liang, Shidong; Zhao, Shuzhi; Lu, Chunxiu; Ma, Minghui
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2016

> In uncontrolled bus systems, buses tend to bunch due to the stochastic nature of traffic flows and passenger demand at bus stops. Although schedules and priori target methods introduce sladc time to delay buses at control points to maintain constant headways between successive buses, too much slack required delay passengers on-board. In addition, these methods focus on regular headways and do not consider the rates of convergence of headways after disturbances. We propose a self-adaptive control scheme to equalize the headways of buses with little slack in a single line automatically. The proposed method only requires the information from the current bus at the control point and both its leading and following buses. This elegant method is shown to regulate headways faster than existing methods. In addition, compared to previous self-equalizing methods, the proposed method can improve the travel time of buses by about 12%, while keeping the waiting time of passengers almost the same.

43. Improving bus service reliability: The Singapore experience

1. Leong, Waiyan; Goh, Karen; Hess, Stephane; Murphy, Paul
2. RESEARCH IN TRANSPORTATION ECONOMICS
3. 2016

> In February 2014, Singapore embarked on a 2-year trial of a Bus Service Reliability Framework (BSRF) to improve en-route bus regularity and reduce instances of bus bunching and prolonged waiting times. Based on London's Quality Incentive Contract, the Singapore model also imposes penalties or provides incentives to operators for increases/reductions of Excess Wait Time (EWT) beyond a certain route specific baseline. Drawing on insights derived from research on performance-based contracts, this

> paper describes some key considerations surrounding this particular innovation in Singapore's overall bus regulatory framework. We also discuss an important advancement in our understanding Of how bus users value reliability improvements through estimates obtained from stated preference data. At the same time, early indications from the trial have been encouraging. (C) 2016 Elsevier Ltd. All rights reserved.

44. Real-Time Bus Holding Control on a Transit Corridor Based on Multi-Agent Reinforcement Learning

1. Chen, Weiya; Zhou, Kunlin; Chen, Chunxiao
2. 2016 IEEE 19TH INTERNATIONAL CONFERENCE ON INTELLIGENT TRANSPORTATION SYSTEMS (ITSC)
3. 2016

> Bus holding is the most used control strategy to improve bus service reliability. This paper presents a coordinated holding control framework based on multi-agent reinforcement-learning (MARL-H) to mitigate bus bunching in real-time on a bus corridor. The MARL-H framework depicts a combination of agents and methods to make decision of coordinated holdings. Coordination Graphs (CGs) are introduced in automatically selecting the coordinated holding actions in case of multiple buses dwelling at stops. Sparse Cooperative Q-learning algorithms are developed to obtain the joint coordinated holding actions due to the particularity of the sparsely structured graphs. The performance of the proposed method is evaluated by simulations. The results show the advantages of the MARL-H framework for the coordinated holding control in real-time. The proposed method could be embedded in an advanced public transportation system to improve bus operation performance.

45. Bus travel time prediction under high variability conditions

1. Reddy, Kranthi Kumar; Kumar, B. Anil; Vanajakshi, Lelitha
2. CURRENT SCIENCE
3. 2016

> Bus travel times are prone to high variability, especially in countries that lack lane discipline and have heterogeneous vehicle profiles. This leads to negative impacts such as bus bunching, increase in passenger waiting time and cost of operation. One way to minimize these issues is to accurately predict bus travel times. To address this, the present study used a model-based approach by incorporating mean and variance in the formulation of the model. However, the accuracy of prediction did not improve significantly and hence a machine learning-based approach was considered. Support vector machines were used and prediction was done using. v-support vector regression with linear kernel function. The proposed scheme was implemented in Chennai using data collected from public transport buses fitted with global positioning system. The performance of the proposed method was analysed along the route, across subsections and at bus stops. Results show a clear improvement in performance under high variance conditions.

46. Multiperiod Bus Timetabling

1. Ibarra-Rojas, Omar J.; Lopez-Irarragorri, Fernando; Rios-Solis, Yasmin A.
2. TRANSPORTATION SCIENCE
3. 2016

> The timetabling subproblem of bus transit network planning determines the departure times for all trips of the lines along the entire day. Most of the public transport networks consider planning periods identical for all lines. In this study we drop this strong assumption by introducing specific periods for each line, which is more realistic. Thus, we propose the multiperiod synchronization bus timetabling (MSBT) problem, which specifies the departure times of the trips of all lines where each line has its own planning periods along the day, with the objective of optimizing synchronization events: maximize passenger transfers and minimize bus bunching along the network. We propose an integer linear programming formulation for the MSBT problem and analyze the structural properties of this formulation by a constraint propagation methodology. These properties are the basis for different operators that lead to the design of efficient metaheuristics for solving the problem. We empirically obtain high-quality feasible solutions for real size instances and show that by considering a multiperiod approach, synchronization events of trips belonging to different planning periods are not ignored, as it is the case when several single period timetables are merged.

47. Uncertainty in Bus Arrival Time Predictions: Treating Heteroscedasticity With a Metamodel Approach

1. O'Sullivan, Aidan; Pereira, Francisco C.; Zhao, Jinhua; Koutsopoulos, Harilaos N.
2. IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS
3. 2016

> Arrival time predictions for the next available bus or train are a key component of modern traveler information systems (TISs). A great deal of research has been conducted within the intelligent transportation system community in developing an assortment of different algorithms that seek to increase the accuracy of these predictions. However, the inherent stochastic and nonlinear nature of these systems, particularly in the case of bus transport, means that these predictions suffer from variable sources of error, stemming from variations in weather conditions, bus bunching, and numerous other sources. In this paper, we tackle the issue of uncertainty in bus arrival time predictions using an alternative approach. Rather than endeavor to develop a superior method for prediction, we take existing predictions from a TIS and treat the algorithm generating them as a black box. The presence of heteroscedasticity in the predictions is demonstrated and then a metamodel approach is deployed, which augments existing predictive systems using quantile regression to place bounds on the associated error. As a case study, this approach is applied to data from a real-world TIS in Boston. This method allows bounds on the predicted arrival time to be estimated, which give a measure of the uncertainty associated with the individual predictions. This represents to the best of our knowledge the first application of methods to handle the uncertainty in bus arrival times that explicitly takes into account the inherent heteroscedasticity. The metamodel approach is agnostic to the process generating the predictions, which ensures the methodology is implementable in any system.

48. A predictive-control framework to address bus bunching

1. Andres, Matthias; Nair, Rahul
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2017

> Busy bus routes often suffer from buses not arriving at regular intervals but in bunches at bus stops. In this paper we study this bus bunching phenomenon and address it by a combination of data-driven headway prediction and dynamic holding strategies, which allow to modulate buses' dwell times at

> stops to reduce the headway deviation. We formulate time headways as time series and compare several prediction methods by testing on data from a busy bus route in Dublin. Furthermore we review and extend an analytical model of an artificial bus route and discuss stability properties and dynamic holding strategies using both data available at the time and predicted headway data. In a numerical simulation we illustrate how the combination of two simple concepts lead to a promising strategy to reduce bus bunching. (C) 2017 Elsevier Ltd. All rights reserved.

49. Self-coordinating Bus Route System to Avoid Bus Bunching

1. Pattanashetty, Vishal B.; Iyer, Nalini C.; Dinkar, Abhinanadan; Gudi, Supreeta
2. PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON DATA ENGINEERING AND COMMUNICATION TECHNOLOGY, ICDECT 2016, VOL 2
3. 2017

> This paper elucidates the problem on bus bunching and the proposed solution to the problem. The motive is to consider the density of passengers and schedule the bus based on the density. The system is capable of considering the density by user-friendly mobile application. The mobile application is accessible within the personal area communication range of the bus terminus. The whole system is controlled by a low power, highly sustainable, and secured wireless technology. The main advantage of this proposal is to reduce unnecessary running of the buses, by which the fuel consumption is reduced and passengers need not wait for a longer time for the buses. The outcome of this result is to establish a well-maintained public transportation by reducing the problem of bus bunching.

50. Using Automatic Vehicle Location Data to Model and Identify Determinants of Bus Bunching

1. Rashidi, Soroush; Ranjitkar, Prakash; Csaba, Orosz; Hooper, Andy
2. WORLD CONFERENCE ON TRANSPORT RESEARCH - WCTR 2016
3. 2017

> Bunching is recognized as one of the deteriorating factors affecting the performance of public transport networks. In this study, for the first time, Gene Expression Programming (GEP) and Decision Tree (DT) methods are utilized to estimate and model bus bunching. These methods are well equipped for dealing with nonlinearity and solving complex problems. The proposed models are compared against well-known Logistic Regression (LOR) models. Different spatial and temporal independent variables such as: bus dwell time, intersection delay, schedule deviation, bus stop spacing and bus stop closeness are used to model and study bus bunching in a real-life example in Auckland, New Zealand. Schedule deviation was determined to be the most influential factor for bus bunching occurrence. The DT method performed better in estimation of bus bunching occurrence compared to the GEP and LOR models. The LOR model inflates minor fluctuations and is prone to overestimation, reducing its predictive performance. (C) 2017 The Authors. Published by Elsevier B.V.

51. Modelling bus bunching and holding control with vehicle overtaking and distributed passenger boarding behaviour

1. Wu, Weitiao; Liu, Ronghui; Jin, Wenzhou
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2017

> Headway fluctuation and bus bunching are commonly observed in transit operations, while holding control is a proven strategy to reduce bus bunching and improve service reliability. A transit operator would benefit from an accurate forecast of bus propagation in order to effectively control the system. To this end, we propose an 'ad-hoc' bus propagation model taking into account vehicle overtaking and distributed passenger boarding (DPB) behaviour. The latter represents the dynamic passenger queue swapping among buses when bunching at bus stops occurs and where bus capacity constraints are explicitly considered. The enhanced bus propagation model is used to build the simulation environment where different holding control strategies are tested. A quasi first-depart-first-hold (FDFH) rule is applied to the design of schedule- and headway-based holding control allowing for overtaking, with the objective to minimise the deviation from the targeted headway. The effects of control strategies are tested in an idealised bus route under different operational setting and in a real bus route in Guangzhou. We show that when the combined overtaking and queue-swapping behaviour are considered, the control strategies can achieve better headway regularity, less waiting time and less on-board travel time than their respective versions without overtaking and DPB. The benefit is even greater when travel time variability is higher and headway is smaller, suggesting that the control strategies are preferably deployed in high-frequency service. (C) 2017 Elsevier Ltd. All rights reserved.

52. A connected-vehicle-based dynamic control model for managing the bus bunching problem with capacity constraints

1. Luo, Xia; Liu, Shuozhi; Jin, Peter J.; Jiang, Xiaowen; Ding, Hongfei
2. TRANSPORTATION PLANNING AND TECHNOLOGY
3. 2017

> This paper describes a connected-vehicle-based system architecture which can provide more precise and comprehensive information on bus movements and passenger status. Then a dynamic control method is proposed using connected vehicle data. Traditionally, the bus bunching problem has been formulated into one of two types of optimization problem. The first uses total passenger time cost as the objective function and capacity, safe headway, and other factors as constraints. Due to the large number of scenarios considered, this type of framework is inefficient for real-time implementation. The other type uses headway adherence as the objective and applies a feedback control framework to minimize headway variations. Due to the simplicity in the formulation and solution algorithms, the headway-based models are more suitable for real-time transit operations. However, the headway-based feedback control framework proposed in the literature still assumes homogeneous conditions at all bus stations, and does not consider restricting passenger loads within the capacity constraints. In this paper, a dynamic control framework is proposed to improve not only headway adherence but also maintain the stability of passenger load within bus capacity in both homogenous and heterogeneous situations at bus stations. The study provides the stability conditions for optimal control with heterogeneous bus conditions and derives optimal control strategies to minimize passenger transit cost while maintaining vehicle loading within capacity constraints. The proposed model is validated with a numerical analysis and case study based on field data collected in Chengdu, China. The results show that the proposed model performs well on high-demand bus routes.

53. Dynamical Modeling and Predictive Control of Bus Transport Systems: A Hybrid Systems Approach

1. Sirmatel, I. I.; Geroliminis, N.
2. IFAC PAPERSONLINE

3. 2017

> Bus operations, due to their unstable nature, are inefficient when left uncontrolled with respect to retaining headways. Irregularities such as bus bunching lead to loss of time and decrease bus service quality. Development of bus transport system management schemes to avoid bus bunching and improve performance are of high importance, and has thus been the focus of many works in the public transport systems literature. Motivated by the importance of developing bus control strategies for improving performance, and specifically by the lack of a detailed but computationally efficient mathematical model describing bus transport system dynamics in the literature (which can facilitate model-based control design), we propose a mixed logical dynamical model of a single loop bus transport system, which involves both continuous (e.g., bus positions) and binary (e.g., the state of a bus regarding whether it is holding at a certain stop or not) states. Furthermore, we develop a hybrid model predictive control scheme with actuation via bus speeds, which can regularize headways and improve bus service quality. Performance of the predictive controller is evaluated via simulation experiments using the proposed model, where the passenger demands and maximum bus speeds are extracted from data collected from the bus network of the city of Fribourg. Results indicate the potential of the proposed controller in avoiding bus bunching and decreasing passenger travel times.

54. Probabilistic Prediction of Bus Headway Using Relevance Vector Machine Regression

1. Yu, Haiyang; Wu, Zhihai; Chen, Dongwei; Ma, Xiaolei
2. IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS
3. 2017

> Bus headway regularity heavily affects transit riders' attitude for choosing public transportation and also serves as an important indicator for transit performance evaluation. Therefore, an accurate estimate of bus headway can benefit both transit riders and transit operators. This paper proposed a relevance vector machine (RVM) algorithm to predict bus headway by incorporating the time series of bus headways, travel time, and passenger demand at previous stops. Different from traditional computational intelligence approaches, RVMcan output the probabilistic prediction result, in which the upper and lower bounds of a predicted headway within a certain probability are yielded. An empirical experiment with two bus routes in Beijing, China, is utilized to confirm the high precision and strong robustness of the proposed model. Five algorithms [support vector machine (SVM), genetic algorithm SVM, Kalman filter, k-nearest neighbor, and artificial neural network] are used for comparison with the RVM model and the result indicates that RVM outperforms these algorithms in terms of accuracy and confidence intervals. When the confidence level is set to 95%, more than 95% of actual bus headways fall within the prediction bands. With the probabilistic bus headway prediction information, transit riders can better schedule their trips to avoid late and early arrivals at bus stops, while transit operators can adopt the targeted correction actions to maintain regular headway for bus bunching prevention.

55. Simulation-Based Optimization in a Bidirectional A/B Skip-Stop Bus Service

1. Huang, Qingxia; Jia, Bin; Jiang, Rui; Qiang, Shengjie
2. IEEE ACCESS
3. 2017

> A two-way bus corridor system always suffers severe demand imbalance between their two operational directions during the peak hours. This paper intends to minimize the average passenger travel time by applying the A/B skip-stop strategy in such an imbalance situation. This strategy defined three types of stations: A , B , and AB . In the service, the buses depart alternately from the original station as type A and B , and A (or B) buses serve A (or B) stations, as well as AB stations. Then the problem becomes determining the skip-stop patterns for both directions. A heuristic genetic algorithm is adopted to solve this problem with a kernel of a precise simulation model depicting the bus system. Finally, we apply the optimization method to a realistic bus corridor of BRT line 1 in Beijing, China. Results demonstrate that the bidirectional A/B skip-stop service prevails over the unidirectional services applying A/B skip-stop only on one direction, and the common used regular service visiting all stations. It is certificated that the bidirectional skip-stop service reduces bus bunching, yields a more balanced bus load and provides a smooth bus service with lower cycle time and variability. Moreover, a sensitivity analysis is conducted to show the impacts of some key attributes on potential benefits of bidirectional skip-stop service. Finally, the elastic demand case where transferring passengers may change their origins or destinations has been discussed.

56. The Bus Bunching Problem: Empirical Findings from Spatial Analytics

1. Iliopoulou, Christina; Milioti, Christina; Vlahogianni, Eleni; Kepaptsoglou, Konstantinos; Sanchez-Medina, Javier
2. 2018 21ST INTERNATIONAL CONFERENCE ON INTELLIGENT TRANSPORTATION SYSTEMS (ITSC)
3. 2018

> Service regularity is one of the most significant performance indicators for public transport routes, typically measured through headway adherence. When headway deviations become too large and corresponding headways very small, bus bunching typically occurs. In these cases, passengers experience larger waiting times and overcrowding and an overall poor level of service. This paper aims to gain insight on frequent patterns of bus bunching using spatial analytics. Local and global spatial autocorrelation tests are performed on real world Automatic Vehicle Location (AVL) data to investigate spatial structures in the data. The spatio-temporal variations of bus bunching patterns throughout the day are further modeled using the ST-DBSCAN algorithm. Results show that the last few stops of each route exhibit statistically significant spatial autocorrelation with respect to the frequency of bunching, while the duration of bunching events is longer for route segments located in the central business district. Spatio-temporal clustering indicates that bunching is observed at a higher number of stops during peak traffic periods.

57. Modeling bus bunching: a comprehensive approach accounting for transit demand and traffic flows

1. Hu, Mao-Bin; Simoni, Michele D.; Claudel, Christian G.
2. 2018 21ST INTERNATIONAL CONFERENCE ON INTELLIGENT TRANSPORTATION SYSTEMS (ITSC)
3. 2018

> Headway fluctuations and bus bunching are commonly observed phenomena in transit operations. In this article, we extend the fast traffic flow solver previously proposed for simulating moving bottlenecks to account for transit demand and traffic flows together. The buses are treated as moving bottlenecks in the traffic flow as their dynamics are affected by surrounding traffic, and vice versa. The dynamics of passengers are integrated to reproduce buses operations. Thanks to a semi-analytical approach, we are

> able to simulate some important aspects of real-life corridors, such as the buses obstructive effect on the surrounding traffic flow, and the environmental traffic effects to the bus bunching phenomenon and passenger waiting time. One can expect that this simulation framework can be employed for transit operation optimization problems where fast and accurate solutions are required.

58. Considering passenger choices and overtaking in the bus bunching problem

1. Sun, Wenzhe; Schmoecker, Jan-Dirk
2. TRANSPORTMETRICA B-TRANSPORT DYNAMICS
3. 2018

> Bus bunching is a well-known phenomenon on many bus routes where an initial delay to one service can disturb the whole schedule due to resulting differences in dwell times of subsequent buses at stops. This paper deals with the passenger behaviour when there is more than one bus serving the stop, focusing on their choices and possible switching actions from the queue of the bus they are waiting to board. A parameter is introduced to denote the percentage of passengers boarding the front bus of two buses boarding at the same time. Cases when overtaking is allowed or not are distinguished as this will also influence the passenger behaviour. A set of discrete state equations is then implemented to obtain the departure times of the buses following the occurrence of an exogenous delay to one of the buses. Evaluation indices are introduced to measure the performance of the bus service along a corridor under different levels. We show that it is advantageous to keep the percentage of passengers boarding the front bus low. Beside, overtaking is a favourable counter-measure against comparatively high front-bus preference.

59. Two-way-looking self-equalizing headway control for bus operations

1. Zhang, Shuyang; Lo, Hong K.
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2018

> Headway variations between successive buses, which lead to bus bunching, is undesirable for both passengers and bus operators, instigating longer average passenger waiting times and capacity underutilization of buses bunched together. Limiting bus bunching, hence, is important for urban bus operations. In this study, we analyze a two-way-looking self equalizing control method for both deterministic and stochastic running times, derive its convergence properties, study the knock-on effect, and optimize its control parameter as a function of the number of buses operating in the route. By comparing the headways from both upstream and downstream of the control point, the control scheme will hold buses, if needed, at the control point to gradually restore the common headway of the system. By utilizing properties of the headway transition matrices associated with the control scheme, we prove that the bus headways will self-equalize under deterministic travel time. In addition, under the context of stochastic travel time variations, we prove that the headway variance of all buses will be reduced to a certain value by the control scheme. Further, we analyze the headway control parameter to determine its optimal value and adopt the scheme for dynamic control. Finally, numerical simulations are conducted to illustrate the performance of this control scheme, with promising results.

60. Optimally combined headway and timetable reliable public transport system

1. Varga, Balazs; Tettamanti, Tamas; Kulcsar, Balazs

2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2018

> This paper presents a model-based multiobjective control strategy to reduce bus bunching and hence improve public transport reliability. Our goal is twofold. First, we define a proper model, consisting of multiple static and dynamic components. Bus-following model captures the longitudinal dynamics taking into account the interaction with the surrounding traffic. Furthermore, bus stop operations are modeled to estimate dwell time. Second, a shrinking horizon model predictive controller (MPG) is proposed for solving bus bunching problems. The model is able to predict short time-space behavior of public transport buses enabling constrained, finite horizon, optimal control solution to ensure homogeneity of service both in time and space. In this line, the goal with the selected rolling horizon control scheme is to choose a proper velocity profile for the public transport bus such that it keeps both timetable schedule and a desired headway from the bus in front of it (leading bus). The control strategy predicts the arrival time at a bus stop using a passenger arrival and dwell time model. In this vein, the receding horizon model predictive controller calculates an optimal velocity profile based on its current position and desired arrival time. Four different weighting strategies are proposed to test (i) timetable only, (ii) headway only, (iii) balanced timetable - headway tracking and (iv) adaptive control with varying weights. The controller is tested in a high fidelity traffic simulator with realistic scenarios. The behavior of the system is analyzed by considering extreme disturbances. Finally, the existence of a Pareto front between these two objectives is also demonstrated.

61. Understanding Transit System Performance Using AVL-APC Data: An Analytics Platform with Case Studies for the Pittsburgh Region

1. Pi, Xidong; Egge, Mark; Whitmore, Jackson; Qian, Zhen (Sean); Silbermann, Amy
2. JOURNAL OF PUBLIC TRANSPORTATION
3. 2018

> This paper introduces a novel transit data analytics platform for public transit planning, assessing service quality and revealing service problems in high spatiotemporal resolution for public transit systems based on Automatic Passenger Counting (APC) and Automatic Vehicle Location (AVL) technologies. The platform offers a systematic way for users and decision makers to understand system performance from many aspects of service quality, including passenger waiting time, stop-skipping frequency, bus bunching level, bus travel time, on-time performance, and bus fullness. The AVL-APC data from September 2012 to March 2016 were archived in a database to support the development of a user-friendly web application that allows both users and managers to interactively query bus performance metrics for any bus routes, stops, or trips for any time period. This paper demonstrates a case study using the platform to examine bus bunching in a transit system operated by the Port Authority of Allegheny County (PAAC) in Pittsburgh. It is found that the incidence of bus bunching is heavily impacted by the location on the route as well as the time of day, and the bunching problem is more severe for bus routes operating in mixed traffic than for bus rapid transit, which operates along a dedicated busway. Furthermore, a second case study is presented with a comprehensive analysis on a representative route in Pittsburgh under schedule changes. Suggestions for operation of this route to improve service quality are proposed based on the data analytics results.

62. Mixed logical dynamical modeling and hybrid model predictive control of public transport operations

1. Sirmatel, Isik Ilber; Geroliminis, Nikolas
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2018

> Bus transport systems cannot retain scheduled headways without feedback control due to their unstable nature, leading to irregularities such as bus bunching, and ultimately to increased service times and decreased bus service quality. Traditional anti-bunching methods considering only regularization of spacings might unnecessarily slow down buses en route. In this work a detailed but computationally lightweight dynamical model of a single line bus transport system involving both continuous and binary states is developed. Furthermore a hybrid model predictive control (MPC) scheme is proposed, with a dual objective of regularizing spacings and improving speed of bus service operations. Performance of the predictive controller is compared with I- and PI-controllers via extensive simulations using the proposed model. Results indicate the potential of the hybrid MPC in avoiding bus bunching and decreasing passenger delays inside and outside the buses. (C) 2018 Elsevier Ltd. All rights reserved.

63. Translating research to practice: Implementing real-time control on high-frequency transit routes

1. Berrebi, Simon J.; Crudden, Sean Og; Watkins, Kari E.
2. TRANSPORTATION RESEARCH PART A-POLICY AND PRACTICE
3. 2018

> On high-frequency routes, buses tend to bunch together, creating gaps in service and causing undue passenger waiting time. There are many approaches to solving the bus bunching problem in the literature but there lacks empirical analysis on practical implementation. In this study, a real-time holding method from the literature was implemented on three high-frequency transit routes, the Atlanta Streetcar and the Georgia Tech Red Route in Atlanta, GA, and the VIA Route 100 in San Antonio, TX. The performance of the method was evaluated in terms of headway stability, holding time, and mean passenger waiting time. The method was found to improve headway stability compared to the schedule, but required longer holds in some cases. Overall, the holding method reduced the waiting time of passengers at stops in all three case studies. The challenges associated with location data quality, prediction accuracy, the human element and the surrounding environment are discussed and strategies to address them are recommended.

64. Comparing bus holding methods with and without real-time predictions

1. Berrebi, Simon J.; Hans, Etienne; Chiabaut, Nicolas; Laval, Jorge A.; Leclercq, Ludovic; Watkins, Kari E.
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2018

> On high-frequency routes, transit agencies hold buses at control points and seek to dispatch them with even headways to avoid bus bunching. This paper compares holding methods used in practice and recommended in the literature using simulated and historical data from Tri-Met route 72 in Portland, Oregon. We evaluated the performance of each holding method in terms of headway instability and mean holding time. We tested the sensitivity of holding methods to their parameterization and to the number of control points. We found that Schedule-Based methods require little holding time but are unable to stabilize headways even when applied at a high control point density. The Headway-Based

> methods are able to successfully control headways but they require long holding times. Prediction-Based methods achieve the best compromise between headway regularity and holding time on a wide range of desired trade-offs. Finally, we found the prediction-based methods to be sensitive to prediction accuracy, but using an existing prediction method we were able to minimize this sensitivity. These results can be used to inform the decision of transit agencies to implement holding methods on routes similar to TriMet 72. Published by Elsevier Ltd.

65. Dynamic bus substitution strategy for bunching intervention

1. Petit, Antoine; Ouyang, Yanfeng; Lei, Chao
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2018

> Bus headways are typically susceptible to external disturbances (e.g., due to traffic congestion, clustered passenger arrivals, and special passenger needs), which create gaps in the system that grow eventually into bunching. Although many control strategies, such as static and dynamic holding strategies, have been implemented to mitigate the effects of unreliable bus schedules, most of them would impose longer dwell times on the passengers. In this paper, we investigate the potential of an alternative bus substitution strategy that is currently implemented by some transit agencies in an ad-hoc manner. In this strategy, the agency deploys a fleet of standby buses to take over service from any early or late buses so as to contain deviations from schedule, and the intention is to impose minimum penalties on the onboard passengers. We develop a discrete-time infinite-horizon approximate dynamic programming approach to find the optimal policy to minimize the overall agency and passenger costs. It is shown through numerical examples that schedule deviations can be controlled by regularly inserting standby buses as substitutions. In some implementation scenarios, the proposed strategy holds the potential to achieve comparable performance with some of the most advanced strategies, and to outperform the conventional slack-based schedule control scheme. In light of the emerging opportunities associated with autonomous driving, the performance of the proposed strategy can become even stronger due to the reduction in costs for keeping the fleet of standby buses.

66. Hybrid Model Predictive Control of Bus Transport Systems

1. Sirmatel, Isik Ilber; Geroliminis, Nikolas
2. 2018 EUROPEAN CONTROL CONFERENCE (ECC)
3. 2018

> Schedule instability adversely affects the performance of bus transport systems. Bus bunching and similar irregularities decrease quality of bus services and increase travel times. In this regard, bus system management schemes are of high importance. Motivated by the potential impact of developing advanced bus control schemes on transportation practice, in this paper a hybrid model predictive control scheme with actuation via bus speeds is developed, which can regularize headways and improve bus service quality. The controller extends upon earlier work by considering detailed dynamics of the interactions between buses and stops via passenger flows. Performance of the controller is compared with a no control case and a PI controller via simulation experiments, conducted with a recently proposed mixed logical dynamical bus loop model involving both continuous (e.g., bus positions) and binary (e.g., the state of a bus regarding whether it is holding at a certain stop or not)

> states. Results showcase the capability of the proposed controller in regularizing headways, avoiding bus bunching and decreasing passenger travel times.

67. Improving Bus Operations through Integrated Dynamic Holding Control and Schedule Optimization

1. Liu, Shuozhi; Luo, Xia; Jin, Peter J.
2. JOURNAL OF ADVANCED TRANSPORTATION
3. 2018

> Bus bunching can lead to unreliable bus services if not controlled properly. Passengers will suffer from the uncertainty of travel time and the excessive waiting time. Existing dynamic holding strategies to address bus bunching have two major limitations. First, existing models often rely on large slack time to ensure the validity of the underlying model. Such large slack time can significantly reduce the bus operation efficiency by increasing the overall route travel times. Second, the existing holding strategies rarely consider the impact on the schedule planning. Undesirable results such as bus overloading issues arise when the bus fleet size is limited. This paper explores analytically the relationship between the slack time and the effect of holding control. The optimal slack time determined based on the derived relationship is found to be ten times smaller than in previous models based on numerical simulation results. An optimization model is developed with passenger-orient objective function in terms of travel cost and constraints such as fleet size limit, layover time at terminals, and other schedule planning factors. The optimal choice of control stops, control parameters, and slack time can be achieved by solving the optimization. The proposed model is validated with a case study established based on field data collected from Chengdu, China. The numerical simulation uses the field passenger demand, bus average travel time, travel time variance of road segments, and signal timings. Results show that the proposed model significantly reduce passengers average travel time compared with existing methods.

68. Optimal headway merging for balanced public transport service in urban networks

1. Varga, Balazs; Tettamanti, Tamas; Kulcsar, Balazs
2. IFAC PAPERSONLINE
3. 2018

> This paper presents a velocity control/advise algorithm relying on vehicle-to-vehicle communication, to ensure the headway homogeneity of buses on a joint corridor, i.e. when multiple lines merge and travel on the same route. The proposed control method first schedules merging buses prior to entering a common line. Second, based on the position and velocity of the bus ahead of the controlled one, a shrinking horizon model predictive controller (MPC) calculates a proper velocity profile for the merging bus. The model is able to predict short time space behavior of public transport buses enabling constrained, finite horizon, optimal control solution to reach the merging point with equidistant headways, taking all buses from different lines into account. The controller is tested in a high fidelity traffic simulator with realistic scenarios.

69. Los Angeles Metro Bus Data Analysis Using GPS Trajectory and Schedule Data (Demo Paper)

1. Kien Nguyen; Yang, Jingyun; Lin, Yijun; Lin, Jianfa; Chiang, Yao-Yi; Shahabi, Cyrus

2. 26TH ACM SIGSPATIAL INTERNATIONAL CONFERENCE ON ADVANCES IN GEOGRAPHIC INFORMATION SYSTEMS (ACM SIGSPATIAL GIS 2018)
3. 2018

With the widespread installation of location-enabled devices on public transportation, public vehicles are generating massive amounts of trajectory data in real time. However, using these trajectory data for meaningful analysis requires careful considerations in storing, managing, processing, and visualizing the data. Using the location data of the Los Angeles Metro bus system, along with publicly available bus schedule data, we conduct a data processing and analyses study to measure the performance of the public transportation system in Los Angeles utilizing a number of metrics including travel-time reliability, on-time performance, bus bunching, and travel-time estimation. We demonstrate the visualization of the data analysis results through an interactive web-based application. The developed algorithms and system provide powerful tools to detect issues and improve the efficiency of public transportation systems.

70. Integrating Bus Holding Control Strategies and Schedule Recovery: Simulation-Based Comparison and Recommendation

1. Wu, Weitiao; Liu, Ronghui; Jin, Wenzhou
2. JOURNAL OF ADVANCED TRANSPORTATION
3. 2018

In the absence of control strategies, headway fluctuation and bus bunching are commonly observed in transit operation due to the stochastic attributes such as travel time and passenger demand. Existing research on real-time control largely focused on developing operational tactics to maintain bus arrival regularity at stops without fully considering the effect of schedule recovery. This paper investigates the effect of bus driver behavior on bus holding control strategies and more specifically their effort in catching up with schedule in case of delay, i.e., schedule recovery. To this end, this paper first proposes a bus propagation model with capacity constraint to simulate the evolution of bus trajectories along a fixed route. It proceeds to explicitly incorporate both holding control actions and schedule recovery effect into the bus propagation model. Using simulation for a high-frequency bus line in Guangzhou, China, schedule-(SH) and headway-based holding (HH) control strategies are compared under various operational settings in the context of schedule recovery. These comparisons show that SH performs better under certain conditions, and SH generally benefits more from schedule recovery than HH. These results provide insights into the bus stop layout design and implementation of holding methods in the context of cruising guidance.

71. Prediction of Bus Bunching Using Smart Card Data

1. Jiang, Rui-Sen; Hu, Da-Wei; Wu, Xue
2. CICTP 2019: TRANSPORTATION IN CHINA-CONNECTING THE WORLD
3. 2019

With the rapid development of economy and society, congestion in cities is increasing and headway for public transport is unstable. Therefore, bus bunching is occurring in the course of bus operation, which leads to unreliable service problems such as increased overall waiting time. Under the premise of the widely used smart card, the research takes a single bus line as the object and studies it with the historical data of the smart card. A real-time model of passengers waiting at bus stops is established

> based on the data of bus speed and historical data. Moreover, the prediction result is used to predict the bus bunching. This paper will verify the efficiency and feasibility of the model by numerical examples. The study's results show that the prediction model of bus bunching based on smart card data can predict the condition during bus operation accurately and discover potential problems in time.

72. Modeling bus bunching using massive location and fare collection data

1. Arriagada, Jacqueline; Gschwender, Antonio; Munizaga, Marcela A.; Trepanier, Martin
2. JOURNAL OF INTELLIGENT TRANSPORTATION SYSTEMS
3. 2019

> Bus bunching is a well-known phenomenon for operators, users and regulators of high-frequency bus services. Bus operations are usually affected by increasing differences in the time intervals (headways) between consecutive buses. The effect of this variability is that buses tend to group into bunches of two or more, which severely affects the quality of service and the operational efficiency. The aim of this paper is to analyze which factors are associated to the phenomenon, using massive data from high-frequency services available in Santiago (Chile) and common-route services in Gatineau (Canada). The data is obtained from the bus GPS and AFC systems and are processed to obtain headways between buses. Using data from one week, we develop models to explain the variation of the continuous and discrete indicators of bus bunching as a function of variables related to the operation, variables related to the demand structure, and variables related to the infrastructure. Some of the factors that contribute to increase bus bunching are: stops located toward the end of the route, high scheduled frequency, irregular bus dispatch headways, non-homogeneous fleet, high demand, and high variability of demand. The results are useful for the design of quality indexes to measure bunching in bus operations, and for the design and operation of bus routes, taking into consideration the potential bus bunching problems.

73. Coordinated Control Strategy for Multi-Line Bus Bunching in Common Corridors

1. Zhou, Xuemei; Wang, Yehan; Ji, Xiangfeng; Cottrill, Caitlin
2. SUSTAINABILITY
3. 2019

> Improving the sharing rate of public transportation is an important content for the sustainable development of urban transportation. However, bus bunching, a common phenomenon during transit operation, makes negative effects on reliability and service level of the bus system. In most urban centers in China, many bus lines usually serve in a corridor. Different buses may interact with each other in the corridor, which may aggravate the bus bunching. However, previous studies on bus bunching focused on single bus service. In addition, with the popularization of bus data acquisition and the maturity of data processing methods, the accuracy of bus bunching research meets more opportunities. In this paper, we proposed a holding strategy based on two-bus cooperative control. A simulation was carried out after preliminarily processing and analyzing the bus operation data of Foshan, Guangdong City. In the simulation, we compared the performance of three different scenarios, which are before control strategy, under the strategy for a single bus line and under the coordinated strategy for multiple bus lines. We contrastively analyze the results of the two strategies from different aspects. The results show that in aspects, such as holding a frequency, holding time, the total running time and the influence on the other bus line, the cooperative holding strategy manifests better. It

> illustrates that it is meaningful to do such a research on the effect of corridor service on bus bunching and add this effect into traditional holding strategy to build a multi-bus cooperative control strategy. The results have important theoretical significance for enriching and completing existing theory and methods of transit system and practical value for improving the service level and attractiveness of buses, increasing the share rate of public transportation, and thus, promoting the sustainable development of cities.

74. Multiline Bus Bunching Control via Vehicle Substitution

1. Petit, Antoine; Lei, Chao; Ouyang, Yanfeng
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2019

> Traditional bus bunching control methods (e.g., adding slack to schedules, adapting cruising speed), in one way or another, trade commercial speed for better system stability and, as a result, may impose the burden of additional travel time on passengers. Recently, a dynamic bus substitution strategy, where standby buses are dispatched to take over service from late/early buses, was proposed as an attempt to enhance system reliability without sacrificing too much passenger experience. This paper further studies this substitution strategy in the context of multiple bus lines under either time-independent or time varying settings. In the latter scenario, the fleet of standby buses can be dynamically utilized to save on opportunity costs. We model the agency's substitution decisions and retired bus repositioning decisions as a stochastic dynamic program so as to obtain the optimal policy that minimizes the system-wide costs. Numerical results show that the dynamic substitution strategy can benefit from the economies of scale by pooling the standby fleet across lines, and there are also benefits from dynamic fleet management when transit demand varies over time. Numerical examples are presented to illustrate the applicability and advantage of the proposed strategy. The substitution strategy not only holds the promise to outperform traditional holding methods in terms of reducing passenger costs, they also can be used to complement other methods to better control very unstable systems.

75. Analysis of Bus Bunching Impact on Car Delays at Signalized Intersections

1. Liang, Shidong; Ma, Minghui
2. KSCE JOURNAL OF CIVIL ENGINEERING
3. 2019

> In uncontrolled bus systems, buses tend to bunch due to the stochastic nature of traffic flows and passenger demands at bus stops. It is widely acknowledged that bus bunching affects transit operations increasing passenger waiting times and variability. However, transit systems are a part of urban transportation systems. Accordingly, buses also affect traffic flows at signalized intersections leading to additional car delays. In this paper, the impact of a linear bus stop on cars caused by one bus is analyzed by employing the shockwave theory. Further, the operating characteristics of bus bunching in terms of the dwell time at a linear stop are analyzed, in both passenger self-organization and stop-skipping control strategy scenarios. Then, the total dwell time of two bunched buses is calculated, considering different passengers on the two successive buses and the difference between boarding and alighting passengers. Finally, the proposed car delays model is simulated with the aid of computer, where numerical analysis is done to obtain the difference in car delays between two evenly spaced buses and two bunched buses. The results of the numerical analysis indicate that bunched

> buses lead to additional car delays compared to evenly spaced buses. In addition, numerical tests are conducted for the self-organization and stop-skipping control strategies considering imbalanced passengers on two successive buses and the difference between boarding and alighting passengers. The results show that larger differences between the numbers of passengers on the two bunched buses and lower differences between the numbers of boarding and alighting passengers lead to larger car delays.

76. Applying the Support Vector Machine to Predicting Headway-Based Bus Bunching

1. Yang, Junjian; Zhou, Hang; Chen, Xuewu; Cheng, Long
2. CICTP 2019: TRANSPORTATION IN CHINA-CONNECTING THE WORLD
3. 2019

> Bus bunching seriously damages the quality of transit service. This paper proposes a predictive approach to detect the occurrence of bus bunching depending on transit smart card data analysis. Several different support vector machine (SVM) algorithms are established to detect bus bunching based on the stop-level headway irregularity. An empirical experiment in Changzhou is conducted to analyze and compare the performances of different algorithms in practical applications. By comparing the prediction accuracy and computation efficiency, the optimal model is determined under different scenarios. The results suggest transit operators should use least squares support vector machine with linear kernel when the size of training dataset is large. Traditional SVM with linear kernel might be a better option for ensuring the prediction accuracy on smaller datasets. This strategy may improve transit service and increase transit ridership.

77. Bus bunching as a synchronisation phenomenon

1. Saw, Vee-Liem; Chung, Ning Ning; Quek, Wei Liang; Pang, Yi En Ian; Chew, Lock Yue
2. SCIENTIFIC REPORTS
3. 2019

> Bus bunching is a perennial phenomenon that not only diminishes the efficiency of a bus system, but also prevents transit authorities from keeping buses on schedule. We present a physical theory of buses serving a loop of bus stops as a ring of coupled self-oscillators, analogous to the Kuramoto model. Sustained bunching is a repercussion of the process of phase synchronisation whereby the phases of the oscillators are locked to each other. This emerges when demand exceeds a critical threshold. Buses also bunch at low demand, albeit temporarily, due to frequency detuning arising from different human drivers' distinct natural speeds. We calculate the critical transition when complete phase locking (full synchronisation) occurs for the bus system, and posit the critical transition to completely no phase locking (zero synchronisation). The intermediate regime is the phase where clusters of partially phase locked buses exist. Intriguingly, these theoretical results are in close correspondence to real buses in a university's shuttle bus system.

78. Modelling bus bunching under variable transit demand using cellular automata

1. Enayatollahi, Fatemeh; Idris, Ahmed Osman; Atashgah, M. A. Amiri
2. PUBLIC TRANSPORT
3. 2019

> Bunching is an operational problem, in bus transit systems with high service frequency, that can lower capacity and affects user satisfaction. The headway (i.e. amount of time between transit vehicle arrivals at a stop) is intrinsically unstable, such that minor disturbances can cause divergence from the scheduled service. In this paper, a bus route is modelled using a one-dimensional cellular automatato investigate the effects of variations in passenger demand on headway instability and thebus bunching phenomenon. Unlike previous research, this study utilizes a typical route design approach, rather than obtaining a phase diagram from random passengerdemand and service frequency. The results show that aone-second decrease in boarding and alighting times per passenger can significantly reduce bunching formation. Such a reduction can be achieved by adopting in-station fare collection methods as opposed to onboard ones, and/or using low-floor buses with wider/multiple doors/channels. In addition, an active mitigation strategy is proposed to prevent theformationof bunching. It is shown that limiting the waiting time for the delayed bus at stops has a great effect on regulating headways and mitigating bunching. Further, to compare different bunching situations, a new index is proposed to evaluate bunching severity (i.e. the number of buses involved in bunching)and intensity(i.e. the overall deviation from the scheduled headway). Using the developed index, it is found that a high Peak-Hour Coefficientacts like an uncontrolled traffic light that regulates the bus flow, resulting in less severe bunching, regardless of the subsequent total delay in the service.

79. Robust dynamic bus controls considering delay disturbances and passenger demand uncertainty

1. Li, Shukai; Liu, Ronghui; Yang, Lixing; Gao, Ziyou
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2019

> This paper proposes a robust dynamic control mechanism for bus transit system, taking account of variations in congestion delays and passenger demand, and combines bus holding and operating speed control strategies. By using a prespecified uncertainty set, we propose a state space model for bus motion with delay disturbances and passenger demand uncertainties. According to the Lyapunov function analysis method, we design a robust dynamic control based on the state-feedback scheme as the bus control to achieve the robust stability of the bus transit system, which effectively reduces the bus bunching phenomenon. Furthermore, we formulate a nonlinear optimal control problem to design the robust optimal bus control, which not only reduces the bus bunching, but also improves the schedule adherence and headway regularity of bus service lines. To handle the complexity of the nonlinear optimal control problem with uncertain parameters and disturbances, we reduce it to a convex optimization problem by the minimization of an upper bound on the objective function. The problem is solved in a polynomial time and satisfies the practical real time requirement. Numerical examples are presented to validate the effectiveness of the model and control methods.

80. An approach to improve the operational stability of a bus line by adjusting bus speeds on the dedicated bus lanes

1. He, Sheng-Xue; Dong, June; Liang, Shi-Dong; Yuan, Peng-Cheng
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2019

> Bus bunching and the unevenly dispersed buses along a bus line commonly appear in an unstable high-frequency bus line system. They will lead to unreliable transit service and long waiting times for many passengers. To resist bus bunching and improve the stability of a bus line, researchers proposed some methods of adjusting the cruising speeds of buses. But their methods generally need to adjust the speeds in all road segments included in the bus line and sometimes need to coordinate the speeds of successively cruising buses. These requirements impede their implementations in practice. This paper presents a new strategy to overcome the above obstacles by adjusting the speeds of buses in the dedicated bus lanes. The regulating speed will be determined by looking multiple critical time points ahead to estimate the influence of the chosen speed. Numerical experiments show that the new strategy can not only stabilize a strongly unstable bus line but also shorten the waiting and riding times of passengers. Several insights have also been uncovered during numerical analyses. a. The set of regulating speeds used by an effective speed adjustment strategy should include refined elements and has a wide range for the values of its elements. b. Only with nonnegative elements in the above set, the strategy will be out of work. c. The more dedicated bus lanes in a bus line, the more effective the strategy becomes. The negligible computational time to supply the proper regulating speed makes the implementation of our strategy practical.

81. Multi-constrained bus holding control in time windows with branch and bound and alternating minimization

1. Gkiotsalitis, Konstantinos; Cats, Oded
2. TRANSPORTMETRICA B-TRANSPORT DYNAMICS
3. 2019

> This work proposes a periodic bus holding control method where the bus holding times of all running trips are computed simultaneously within each optimization time period; thus, increasing the coordination among running buses for avoiding bus bunching. This paper considers the adverse effects of the bus holding control in the in-vehicle travel times of on-board passengers and performs holistic bus holding decisions by modelling the bus holding problem as a discrete, nonlinear, constrained optimization problem. Given the computational complexity of the bus holding problem, an alternating minimization approach is introduced for computing the optimal holding times at each optimization instance. The performance of the periodic control method is evaluated against the performance of event-based control methods using 5-month automated vehicle location and automated passenger count data from bus line 1 in Stockholm for contacting simulation-based experiments.

82. Coordinated control method to self-equalize bus headways: an analytical method

1. Liang, Shidong; Ma, Minghui; He, Shengxue; Zhang, Hu; Yuan, Pengcheng
2. TRANSPORTMETRICA B-TRANSPORT DYNAMICS
3. 2019

> In an uncontrolled bus line, buses tend to bunch due to the stochastic nature of traffic flow and passenger demand at bus stops. Although bus holding has been shown to effectively prevent bus bunching, this control method often fails when disturbances are large and frequent. A coordinated control method combining two control means (bus holding and stop-skipping) is proposed instead of using only one control means. Bus holding and stop-skipping are integrated with the concept of predictive control. Considering the conciseness and convenience in applications, herein, we propose an analytical method to automatically equalize bus headways in a single line by analyzing bus headways

> between both its leading and following buses, as well as the number of waiting passengers at the bus stops. Numerical tests conducted in a simplified scenario and random scenario show that the proposed coordinated control method performs better in terms of headway convergence rate and resisting random disturbance than using bus holding only. Moreover, a set of simulation tests based on an actual bus route showed better performance of the proposed coordinated control method with increasing demand in terms of regulating the bus headway, saving the total travel time, and providing reliable service for passengers.

83. A predictive headway-based bus-holding strategy with dynamic control point selection: A cooperative game theory approach

1. Dai, Zhuang; Liu, Xiaoyue Cathy; Chen, Zhuo; Guo, Renyong; Ma, Xiaolei
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2019

> Bus holding is a widely used control method to regularize bus headways and reduce bus bunching. The method works in such a way by delaying buses at control points if their departure times or headways deviate from the planned ones. However, it may result in reduced bus commercial speeds and increased passenger onboard travel time. To avoid this problem, researchers have suggested that control points be spaced cautiously along the route such that only a few are needed. This study proposes a predictive headway based bus holding strategy with dynamic control point importance ranking and selection based on the cooperative game theory. The framework considers not only individual control points' impact but also the collective group control effects. Specifically, the proposed framework consists of two components: a performance model and a cooperative game model. The performance model predicts headway performances of all running buses when different control point combinations are in effect. Dynamic bus running times and passenger demands are reflected in the model. Then, these headway performances are passed to the cooperative game model with control points being players and improvements in headway performances compared with that under no holding control being the utility function. The game is solved by Myerson value, a concept that extends Shapley value used for the normal cooperative game and considers the cooperation structure and potential worth of coalitions. We use Myerson value to rank the importance of control points on regularizing headways, as it measures the average marginal utility contribution of a control point to all possible coalitions that exclude that point. We prove that Myerson value lies in the Omega-core of the game and thus satisfies allocation efficiency, individual and coalition rationality. The proposed framework is applied to target headway control and two-way-looking self equalizing headway control. Simulation results show that the framework can significantly reduce passenger waiting time and bus headway variation.

84. The impact of bus fleet size on performance of self-equalise bus headway control method

1. Liang, Shidong; Ma, Minghui; He, Shengxue; Zhang, Hu
2. PROCEEDINGS OF THE INSTITUTION OF CIVIL ENGINEERS-MUNICIPAL ENGINEER
3. 2019

> Headway fluctuation and bus bunching are common in transit operations, while holding control is a proven strategy for the reduction of bus bunching. Recently, benefited from the advances in technology and tools, adaptive control method for equalising bus headways on the bus route gradually has become successful. Although this method performs well in regulating the bus operation, it does

> not consider the impact of the number of buses on the bus route. The control method may fail to regulate bus headways due to an insufficient number of buses, despite the control method itself being effective. Therefore, this paper explores the relationship between the number of buses on the bus route and the performance of the self-equalise bus headway control method. A model is proposed to search the suitable number of buses on the bus route by analysing the changes of the bus headway standard deviations with increasing the number of buses. Furthermore, a set of numerical tests were conducted. According to the results of the analysis, under high demand, the performance of the self-equalise bus headway control method is more sensitive to changes of bus number on the bus route.

85. Modelling and managing bus service regularity with influence of prevailing traffic

1. Chow, Andy H. F.; Li, Shuai
2. TRANSPORTMETRICA B-TRANSPORT DYNAMICS
3. 2019

> This paper presents a multi-modal framework for modelling and analysing different headway control strategies for improving bus service regularity. The interaction between buses and their surrounding traffic is captured in a multi-modal system through a Hamilton-Jacobi formulation of kinematic wave model. This paper further presents a set of signal-based strategies which regulate bus headway through adjusting signal timing plans. The results reveal that the capability of regulating bus headway disturbances through utilising traffic signals is important for maximising bus service regularity and coordinating the bus dynamics with surrounding traffic. This study generates new insights on managing bus reliability and multi-modal traffic in busy urban networks.

86. Real-Time Integrated Holding and Priority Control Strategy for Transit Systems

1. Koehler, Luiz Alberto; Seman, Laio Oriel; Kraus, Werner, Jr.; Camponogara, Eduardo
2. IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS
3. 2019

> This paper presents a real-time integrated holding and priority control strategy for bus rapid transit (BRT) and high-frequency segregated transit systems, in a network approach (considering the whole transit circuit). The integrated control strategy implements simultaneously the required bus headway corrections and the bus priority through signalized intersections with the objective of minimizing the total delay of passengers that are onboard and at stops. The developed model, in the form of a mathematical programming problem, presents peculiarities for describing the behavior of BRT and transit systems such as bus capacity, differentiation between passenger boarding and alighting processes in single stops, terminals and stations, and bus priority at signalized intersections. The iterative procedure proposed for solving the optimization problem brings about simplicity and efficiency for real-time applications. The results obtained by simulation for a transit scenario of the trunk line 10 of the city of Blumenau, Santa Catarina, Brazil, show the efficiency of the proposed strategy and potential of practical application.

87. Multiobjective Optimal Formulations for Bus Fleet Size of Public Transit under Headway-Based Holding Control

1. Liang, Shidong; Ma, Minghui; He, Shengxue
2. JOURNAL OF ADVANCED TRANSPORTATION
3. 2019

> In recent years, with the development of advanced technologies for data collection, real-time bus control strategies have been implemented to improve the daily operation of transit systems, especially headway-based holding control which is a proven strategy to reduce bus bunching and improve service reliability for high-frequency bus routes, with the concept of regulating headways between successive buses. This hot topic has inspired the reconsideration of the traditional issue of fleet size optimization and the integrated bus holding control strategy. The traditional headway-based control method only focused on the regulation of bus headways, without considering the number of buses on the route. The number of buses is usually assumed as a given in advance and the task of the control method is to regulate the headways between successive buses. They did not consider the bus fleet size problem integrated with headway-based holding control method. Therefore, this work has presented a set of optimal control formulations to minimize the costs for the passengers and the bus company through calculating the optimal number of buses and the dynamic holding time, taking into account the randomness of passenger arrivals. A set of equations were formulated to obtain the operation of the buses with headway-based holding control or the schedule-based control method. The objective was to minimize the total cost for the passengers and the bus company in the system, and a Monte Carlo simulation based solution method was subsequently designed to solve the optimization model. The effects of this optimization method were tested under different operational settings. A comparison of the total costs was conducted between the headway-based holding control and the schedule-based holding control. It was found that the model was capable of reducing the costs of the bus company and passengers through utilizing headway-based bus holding control combined with optimization of the bus fleet size. The proposed optimization model could minimize the number of buses on the route for a guaranteed service level, alleviating the problem of redundant bus fleet sizes caused by bus bunching in the traditional schedule-based control method.

88. Transit Operation Optimization in the Context of Connected and Automated Vehicles: A Case Study of Beijing

1. Shen, Xuanliang; Ma, Xiaolei; Zhang, Zhao; Su, Yuelong; Dong, Zhenning
2. CICTP 2019: TRANSPORTATION IN CHINA-CONNECTING THE WORLD
3. 2019

> Connected and automated vehicles (CAV) initiatives are revolutionizing the entire transportation society. Not limited in the area of passenger cars, public transit agencies also seek for the possibility of replacing tremendous manpower with the state-of-the-art self-driving technologies. In this study, we developed an optimization model to quantify how the CAV benefits the route-level transit operations if all current non-automated buses are converted into autonomous buses. A bi-objective mixed integer programming model is established to minimize passenger waiting times and maximize passenger flows considering all buses are running on a bus dedicated lane. By taking one actual bus route in Beijing as a case study, we computed the operational performance indicators of non-automated bus based on smart card and GPS data, and compared with the optimized bus routes with CAV technologies. The findings reveal that autonomous buses can significantly reduce vehicle usages, reduce bus bunching, increase passenger loads, and lower average passenger waiting time.

89. Statistical analysis of the stability of bus vehicles based on GPS trajectory data

1. Zhang, Hui; Shi, Baiying; Song, Shuguang; Zhao, Quanman; Yao, Xiangming; Wang, Wei
2. MODERN PHYSICS LETTERS B
3. 2019

> High quality bus service is considered as an efficient way to mitigate traffic congestion in big cities. Global positioning system (GPS) data provide sufficient sources to evaluate the performance of bus vehicles that both passengers and operator concern about. This paper aims to propose a framework to assess the operational performance of bus routes based on the GPS trajectory data collected from Jinan, China. Several important indicators of bus operation including travel time of routes, section running time, dwell time and bus bunching have been studied. The results show that the travel time of routes follow right skewed distributions. Moreover, section running time between two consecutive stations varies in different time period and it is larger in evening peak hours. Additionally, the dwell time has been discussed and the results show that there is no big variation in most stations except some stations, which provides a help to identify the key stations. Furthermore, we propose an approach to detect the bunching points. The results indicate the bunching points are easy to occur in the peak hours and the congested road section.

90. Dynamic control strategy based on passenger choice behavior with real-time information

1. Wang, Wensi; Tian, Zhihui; Jiang, Yonglei; Wu, Lan; Gao, Jianqiao
2. SIMULATION-TRANSACTIONS OF THE SOCIETY FOR MODELING AND SIMULATION INTERNATIONAL
3. 2019

> Real-time control strategies are important methods for high-frequency transit to counteract the effects of bus bunching in passenger waiting time. This paper extends previous literature with the development of an optimization model for multiple lines in a corridor capable of executing a dynamic control strategy based on passenger choice behavior with real-time information. The bi-level model integrates passenger perceptions,service selection, and control strategy effectively. The upper level model is a control model with the objective of minimizing the total waiting time of passengers in the system composed of common lines to decide whether a bus arriving at the hub should be held and its holding time. The lower level model is an allocation model with the utilization of a Nested Logit model to study passenger choice behavior. In addition, a heuristic algorithm is introduced to solve the problem. The effectiveness of the model is evaluated with the data of two lines in Dalian city of China. The results show that the control strategy proposed in this paper outperforms the simple control strategy without passenger choice behavior, where the waiting time of passengers, the number of buses that need to hold, and bus holding time are all reduced.

91. Understanding the factors that influence the probability and time to streetcar bunching incidents

1. Nguyen, Paula; Diab, Ehab; Shalaby, Amer
2. PUBLIC TRANSPORT
3. 2019

> Bunching is a well-known operational problem for transit agencies and it has negative impacts on service quality and users' perception. While there has been a substantial amount of literature about understanding the factors associated with bus bunching and strategies used to mitigate the effects of this problem, there has been little research on streetcar bunching. Although bus and streetcar systems share many similarities, one major difference between the two is that streetcars cannot overtake each other. This makes bunching in streetcar networks more critical to the reliability of the system and an important topic that requires more in-depth understanding. This research aims at understanding the factors that are associated with the likelihood of streetcar bunching and to investigate in greater detail

> the external and internal factors that relate to the time to the initial bunching incident from terminal. To achieve the first goal, the study uses a binary logistic regression model, while it uses an accelerated failure time model to address the second goal. The study utilizes automatic vehicle location system data acquired from the Toronto Transit Commission, the transit provider for the City of Toronto. The models' results show that headway deviations at terminals are related to both an increase in the probability of bunching and an acceleration of the time to bunching. The discrepancy in vehicle types between two successive streetcars also has the same relationship as headway deviations at terminals. This study offers a better understanding of the factors that are associated with streetcar service bunching, which is an important component of transit service reliability.

92. Identifying spatio-temporal patterns of bus bunching in urban networks

1. Iliopoulou, Christina A.; Milioti, Christina P.; Vlahogianni, Eleni I.; Kepaptsoglou, Konstantinos L.
2. JOURNAL OF INTELLIGENT TRANSPORTATION SYSTEMS
3. 2020

> The objective of this paper is to identify hot spots of bus bunching events at the network level, both in time and space, using Automatic Vehicle Location (AVL) data from the Athens (Greece) Public Transportation System. A two-step spatio-temporal clustering analysis is employed for identifying localized hot spots in space and time and for refining detected hot spots, based on the nature of bus bunching events. First, the Spatio-Temporal Density Based Scanning Algorithm with Noise (ST-DBSCAN) is applied to distinguish bunching patterns at the network level and subsequently a k++means algorithm is employed to distinguish different types of bunching clusters. Results offer insights on specific time periods and route segments, where bus bunching events are more likely to occur and, also, on how bus bunching clusters change over time. Further, headway deviation analysis reveals the differences in the characteristics of the various bunching event types per line, showing that routes running on shared corridors experience more issues while underlying causes may vary per line. Collectively, results can help guide practice toward more flexible solutions and control strategies. Indeed, depending on the type of spatio-temporal patterns detected, appropriate improvements in service planning and real-time control strategies may be identified in order to mitigate their negative effects and improve quality of service. In light of emerging electric public transport systems, the proposed framework can be also used to determine preventive strategies and improve reliability in affected stops prior to the deployment of charging infrastructure.

93. Understanding the factors that affect the bus bunching events' duration

1. Iliopoulou, Christina; Vlahogianni, Eleni, I; Kepaptsoglou, Konstantinos
2. 2020 IEEE 23RD INTERNATIONAL CONFERENCE ON INTELLIGENT TRANSPORTATION SYSTEMS (ITSC)
3. 2020

> Dealing with bus bunching is a challenge for bus operators, as it strongly affects perception on the level of service provided by buses. Despite the growing interest on bus bunching, existing studies have focused on its frequency, neglecting potential differences in the intensity of bus bunching events and, thus, in the associated effect on passengers. This study focuses on the duration of bus bunching events, as a measure of both the problem magnitude and its impact on passengers. Hazard-based duration models are employed to bus bunching event data from the Athens Public Transport Network to estimate the effect of and understand the factors that affect bus bunching event durations. The Lognormal Accelerated Failure Time model performs best among parametric models, with deep

> survival analysis achieving superior predictive accuracy. Results show that temporal factors, such as the afternoon peaks and weekends affect bunching duration. Further, physical and operational characteristics of the initial point in a sequence of bus stop instances also have an impact on the duration of bunching. Overall, results can shed light at the contributing factors of bus bunching events duration and help operators prioritize interventions at the level of bus stops.

94. Reduce Bus Bunching with a Real-Time Speed Control Algorithm Considering Heterogeneous Roadway Conditions and Intersection Delays

1. Deng, Ya-Juan; Liu, Xiao-Hong; Hu, Xianbiao; Zhang, Min
2. JOURNAL OF TRANSPORTATION ENGINEERING PART A-SYSTEMS
3. 2020

> This paper investigates bus bunching issues encountered with a single bus line. A real-time speed control model was proposed with the objective of minimizing variations in bus headway. Three cases of a typical road infrastructure for bus lines were studied. Two main factors that influence the stability of bus service-namely, signalized intersection delays and heterogeneous roadway conditions-were studied in the modeling process. In addition, other common variables were considered, including the time required for passengers to board a bus and alight from it. Compared with findings from prior literature, that frequently assumed homogeneous roadway infrastructure conditions and ignored intersection delays. The built model output the degree of speed adjustment required in accordance with different roadway configurations and the congestion level at each road section. A case study was designed to test the performance of the proposed model, based on the data collected from 40 bus stops, on Bus route No. 600 in Xi'an, China. Results showed that the proposed model could effectively restrain the problems posed by headway deviations and reduce travel time for the passengers.

95. Dynamic holding control to avoid bus bunching: A multi-agent deep reinforcement learning framework

1. Wang, Jiawei; Sun, Lijun
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2020

> Bus bunching has been a long-standing problem that undermines the efficiency and reliability of public transport services. The most popular countermeasure in practice is to introduce static and dynamic holding control. However, most previous holding control strategies mainly consider local information with a pre-specified headway/schedule, while the global coordination of the whole bus fleet and its long-term effect are often overlooked. To efficiently incorporate global coordination and long-term operation in bus holding, in this paper we propose a multi-agent deep reinforcement learning (MDRL) framework to develop dynamic and flexible holding control strategies for a bus route. Specifically, we model each bus as an agent that interacts with not only its leader/follower but also all other vehicles in the fleet. To better explore potential strategies, we develop an effective headway-based reward function in the proposed framework. In the learning framework, we model fleet coordination by using a basic actor-critic scheme along with a joint action tracker to better characterize the complex interactions among agents in policy learning, and we apply proximal policy optimization to improve learning performance. We conduct extensive numerical experiments to evaluate the proposed MDRL framework against multiple baseline models that only rely on local information. Our results

> demonstrate the superiority of the proposed framework and show the promise of applying MDRL in the coordinative control of public transport vehicle fleets in real-world operations.

96. Comprehensive Approach to Transfer Synchronization in Public Transit

1. Wu, Zhongjun; An, Kun; Wang, Wei; Currie, Graham; Hu, Xiaojian
2. JOURNAL OF TRANSPORTATION ENGINEERING PART A-SYSTEMS
3. 2020

> The dynamic and uncertain characters of traffic often make bus schedules erratic; therefore, planned synchronized public transit transfers do not always materialize. This research aims at reducing the operational deviation of buses, and thus increasing arrival reliability of vehicles as well as improving the occurrence of direct transfer. To achieve this objective, a mathematical model is developed to calculate the recommended parameters of real-time bus operation strategies according to real-time arrival time deviation data. A case study is conducted to demonstrate the effectiveness of the proposed approach in practice. Results illustrate that adopting this approach reduces the probability of bus bunching from 8.33% to 0, and increases the operational reliability of vehicles, although transit vehicles have a larger delay. Moreover, direct transfer can be guaranteed with our proposed approach.

97. Modeling and Prediction of Bus Operation States for Bunching Analysis

1. Deng, Yajuan; Luo, Xin; Hu, Xianbiao; Ma, Yanfeng; Ma, Rui
2. JOURNAL OF TRANSPORTATION ENGINEERING PART A-SYSTEMS
3. 2020

> Bus bunching deteriorates transit service quality and passengers' experience. The modeling and prediction of bus operation states are essential for improving the quality of transit service. Due to the nature of traffic evolution and state transition, bunching-oriented modeling based on bus operation state is more intuitive when compared with the headway-based modeling approach. This work explicitly predicted bus operation state by modeling the dynamic evolution of different states. Five different bus operation states were defined and classified by the K-means algorithm, and the dynamic state evolution was formulated as a Markov chain model. Finally, a multinomial logistic model was developed to predict the bus operation state. A case study was designed to test the performance of the proposed model based on the Global Positioning System (GPS) trajectory data collected from four bus routes in Xi'an, China. The results showed that the proposed model was able to accurately predict the bus operation states.

98. Two-Way Cooperative Priority Control of Bus Transit with Stop Capacity Constraint

1. Gao, Qian; Zhang, Shuyang; Chen, Guojun; Du, Yuchuan
2. SUSTAINABILITY
3. 2020

> Signal priority control and speed guidance are effective ways to reduce the delay of buses at intersections. Previous work generally focused on the optimization strategy at the intersection area, without simultaneously considering the influence on adjacent downstream bus stops. This probably leads to the size of the passed bus platoon exceeding the capacity of berths and queuing, which in turn causes additional delay to the overall bus travel time. Focusing on this problem, this paper proposes a two-way cooperative control strategy that constrains the size of the upstream platoon. Besides this, to

> avoid bus bunching, no more than two buses from the same route can be admitted in the same platoon. Based on these principles, we modeled how to make buses pass without stopping by simultaneously considering the signal control and speed guidance. Finally, the effectiveness was validated by simulation in Verkehr in Stadten Simulation (VISSIM, German for Traffic in cities-simulation), a microscopic traffic simulator. The results show that compared to the existing methods, which only use signal control, the cooperative strategy reduces the total delay at the intersection and the downstream stop. It alleviates the queuing phenomenon at the downstream bus stop greatly, and the bus arrivals tend to be more uniform, which helps improve the reliability and sustainability of bus services.

99. An optimization-based speed-control method for high frequency buses serving curbside stops

1. Bian, Bomin; Zhu, Ning; Pinedo, Michael; Ma, Shoufeng; Yu, Qinxiao
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2020

> In this paper, an optimization-based speed-control method is proposed to alleviate the adverse effects of bus bunching. This method specifically focuses on one-way line transit corridors with curbside stops and high frequency buses. In such public transit corridors, holding buses at stops may not be suitable for implementation. Instead of holding, we choose to control bus cruising speeds between stops. The relationship between holding and speed-control is discussed. A conventional holding model M0 as well as a model M1, that determines travel times between stops, are considered. In order to make control decisions easy to understand as well as to follow, an improved speed-control model M2 is also proposed. All the models allow for control decisions based on the real-time state of the entire system. The three models are programmed in a rolling horizon scheme within a simulation system. Simulation experiments are conducted to examine these models in different scenarios associated with different levels of traffic randomness. The corresponding results show that, when the traffic is highly variable, the speed-control method can reduce average passenger waiting time by more than 23% while the holding method results in an average passenger waiting time that is almost 2 min longer than when using the speed-control method. So the speed-control model is shown to be more suitable for implementation in practice. Four strategies that can generate more driver-friendly control decisions are further proposed and tested. The practical applications of the proposed speed-control models are discussed.

100. No-boarding buses: agents allowed to cooperate or defect

1. Saw, Vee-Liem; Yue Chew, Lock
2. JOURNAL OF PHYSICS-COMPLEXITY
3. 2020

> We study a bus system with a no-boarding policy, where a 'slow' bus may disallow passengers from boarding if it meets some criteria. When the no-boarding policy is activated, people waiting to board at the bus stop are given the choices of cooperating or defecting. The people's heterogeneous behaviours are modelled by inductive reasoning and bounded rationality, inspired by the El Farol problem and the minority game. In defecting the no-boarding policy, instead of the minority group being the winning group, we investigate several scenarios where defectors win if the number of defectors does not exceed the maximum number of allowed defectors but lose otherwise. Contrary to

> the classical minority game which has N agents repeatedly playing amongst themselves, many real-world situations like boarding a bus involves only a subset of agents who 'play each round', with different subsets playing at different rounds. We find for such realistic situations, there is no phase transition with no herding behaviour when the usual control paramater 2(m)/N is small. The absence of the herding behaviour assures feasible and sustainable implementation of the no-boarding policy with allowance for defections, without leading to bus bunching.

101. A stochastic model for bus injection in an unscheduled public transport service

1. Morales, Diego; Carlos Munoz, Juan; Gazmuri, Pedro
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2020

> Randomness affecting the operation of public transport systems generates significant increments in waiting times. A strategy to deal with this randomness is bus injection, in which buses are kept in specific points along the route ready to be dispatched when an event such as an extremely long headway occurs. In this work, a stochastic model based on the second moment of the headways distribution is developed to determine if one or more buses are worth reserving for injection in a public transport service. A single stop approach is initially used to determine an expression for the optimal headway threshold triggering the injection. Then, a model for the complete service is developed and used to determine when the empty bus should be injected within the headway once the decision to inject it has been taken. We show that the bus should be injected approximately when 57% of the headway has passed. Simulations with real data are used to test the proposed model, proving its accuracy in terms of measuring the impact on waiting times. The results show that reserving a bus to be injected can be better than operating the entire fleet continuously.

102. Hierarchical Control of Electric Bus Lines

1. Lacombe, Remi; Gros, Sebastien; Murgovski, Nikolce; Kulcsar, Balazs
2. IFAC PAPERSONLINE
3. 2020

> In this paper, we propose a hierarchical control strategy for a line of electric buses with the double objective of minimizing energy consumption and providing regular service to the passengers. The state-space model for the buses is formulated in space rather than in time, which alleviates the need for integer decision variables to capture their behavior at bus stops. This enables us to first assemble a fully-centralized multi-objective line problem in the continuous nonlinear optimization framework. It is then reassembled into a hierarchical structure with two levels of control in order to improve on scalability and reliability. This new supervisory structure consists of a centralized line level controller which handles the time headway regularity of the buses, and of decentralized bus level controllers which simultaneously manage the energy consumption of each individual bus. Our method demonstrates good battery energy savings and regularity performances when compared to a classical holding strategy. Copyright (C) 2020 The Authors.

103. Mixed Scheduling Strategy for High Frequency Bus Routes With Common Stops

1. Bie, Yiming; Tang, Ruru; Liu, Zhiyuan; Ma, Dongfang
2. IEEE ACCESS
3. 2020

> Bus routes overlapping would lead to more than one bus entering the stop simultaneously, which may trigger bus bunching. Focusing on high frequency routes with common stops, this paper proposes a mixed scheduling method combining the all-stop service and the stop-skipping service. The method optimizes scheduling strategies for multiple routes by minimizing total passenger travel time. The optimization variables are binary variables reflecting whether the stops in the overlapping area are skipped. Three exciting bus routes are employed for case study. Results show that the proposed method reduces total passenger travel time by 21.4 % compared with the current scheduling strategy.

104. Integrated headway and bus priority control in transit corridors with bidirectional lane segments

1. Seman, Laio Oriel; Koehler, Luiz Alberto; Camponogara, Eduardo; Kraus Jr, Werner
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2020

> The problem of operating exclusive bus corridors that have segments with bidirectional lanes is treated. On these lanes, only one direction of movement is allowed when a bus is present. Such construct requires less road space, which is a scarce resource in dense urban areas, and thus may be the only feasible alternative for the installation of exclusive bus corridors. The system model includes limits on bus passenger capacity. The control method for real-time operation integrates bus headway corrections and bus priority through signalized intersections, while enforcing mutual exclusion of opposing buses on the bidirectional lanes. Effectively, the control avoids bus bunching over the entire corridor and coordinates the passage of opposing buses on bidirectional lanes. The objective is to minimize the total waiting time of passengers, both onboard and at stops. Simulation results indicate the applicability of the integrated holding and priority bidirectional lane control method.

105. Dynamic headway control for high-frequency bus line based on speed guidance and intersection signal adjustment

1. Bie, Yiming; Xiong, Xinyu; Yan, Yadan; Qu, Xiaobo
2. COMPUTER-AIDED CIVIL AND INFRASTRUCTURE ENGINEERING
3. 2020

> To prevent bus bunching, a dynamic headway control method in the V2I (vehicle to infrastructure) environment for a high-frequency route with bus lane is developed. Bus operating speed guidance on the mid-blocks and intersection signal adjustment are two main strategies in the proposed method. A forecasting model of bus travel time under the dynamic control method is developed. The objective function is set up by taking into account differences between actual bus headways and dispatching headways, and the scaling ratios of intersection cycle lengths. The optimization model is solved using genetic algorithm. The proposed method is applied to a real bus route in Meihekou city, China, and compared with the current control plan as well as holding strategy. Results show that the proposed method can reduce bus headway deviations in all investigating periods; negative impacts on cars can be limited by setting reasonable values for the parameters.

106. Pre-Control Strategies for Downstream Bus Service Reliability With Traffic Signal

1. Zhang, Hu; Liang, Shidong; Han, Yin; Ma, Minghui; Leng, Rongmeng
2. IEEE ACCESS
3. 2020

> As an undesired behavior of the transport system, headway fluctuation or even bus bunching reduce reliability of bus stop service for waiting passengers. This paper proposes a pre-control method to improve the balance of service intervals at downstream stop through an adjustment of green time for bus passing, in which priority and delay of bus passing can be achieved. The proposed pre-control strategies at intersection are triggered based on prediction of service intervals at downstream stop to select priority or delay strategy that includes adjusting starting and ending time of green light. Meanwhile, the influence of adjustment of green time on surrounding traffic delay of vehicle is also considered. The traffic delay is estimated for vehicles arriving during phases within associated two signal cycles induced by the signal adjustment. To derive optimal adjustment of green time, a multi-objective function is established and the objectives include deviation of the bus service intervals and traffic average delay. An exhaustive search algorithm is programmed to solve the objective function. The effects of control strategies are tested by numerical experiments based upon a real bus route in Changchun. Results show that the bus service reliability can be improved through a proper signal pre-control and, compared with the single control strategy with only bus delay, the standard deviations of service intervals with the average running time and the stochastic running time are improved by 8.53% and 7.31%, respectively.

107. A Prediction Model for Bus Arrival Time at Bus Stop Considering Signal Control and Surrounding Traffic Flow

1. Zhang, Hu; Liang, Shidong; Han, Yin; Ma, Minghui; Leng, Rongmeng
2. IEEE ACCESS
3. 2020

> The arrival time of bus at the stop is critical data in design of bus operational strategies. Especially for real-time control strategies (i.e., signal priority system), bus arrival time is usually predicted to assess the next bus operation condition in the future (i.e., bus bunching and reliability of transit service) and then can be used as a decision basis of current control actions. The signalized intersection and surrounding traffic are the key factors in bus travel time prediction, but most previous approaches focus on the impact of signal control on bus delay only. This paper proposes a prediction model for arrival time at bus stop under the influence of both upstream signalized intersection and surrounding traffic flow. Considering the affected range of signalized intersection and the dynamic variation of bus speed, bus running processes are evaluated separately (including processes from a given detection point to stop line, through intersection, and from intersection to bus stop). In the proposed models, bus speed is deduced according to the change of traffic density at different locations to reflect the micro-impact of surrounding traffic flow on bus operation. The observed bus travel time is collected from actual investigations at two bus stops incorporating signalized intersection in Jinan City and compared with the predicted travel time in the proposed model. The results show that the proposed model has a low mean relative error. In addition, through the analysis of the maximum relative error, it also can be seen that vehicle queuing with random arrival of vehicles at stop line makes a gap between the prediction and the actual situation, which will be the focus of further research.

108. Simulation-Based Sensitivity Analysis for Evaluating Factors Affecting Bus Service Reliability: A Big and Smart Data Implementation

1. Moosavi, Seyed Mohammad Hossein; Yuen, Choon Wah; Yap, Soon Poh; Onn, Chiu Chuen
2. IEEE ACCESS
3. 2020

> Service quality is a significant concern for both providers and users of public transportation. It is crucial for transit agencies to clearly recognize the causes of unreliability before adapting any improvement strategy. However, evaluation of main causes of bus service unreliability has not been investigated well. Existing studies have three main limitations in context of recognizing causes of service unreliability. First, public transport networks and traffic condition are highly complex systems and most of the existing models are not capable to accurately determine the relationship between service irregularity and impact factors. Second, definition of Big data has been neglected and most of the studies only focused on one source of large scale data set to determine the causes of unreliability. Third, bus service unreliability can impact the users' perception toward the public transport, significantly. It has been recommended by number of studies that bus service reliability should be evaluated from both service providers' and users' perspective. However, the impact of service unreliability from passengers' perception is not well investigated, yet. Consequently, we proposed a novel simulation-based sensitivity analysis to evaluating main causes of bus service unreliability using a combination of three different sources of big data. Moreover, for the first time we developed a simulation model in R studio which is an open source and powerful coding environment. According to the results, the level of reliability in Route U32 showed the highest sensitivity to headway variations. Waiting time can be decreased by 61% if only bus operators can reduce the headway variation by 25% of the actual observed data. Big gap and bus bunching could be almost disappeared by decreasing headway variations. Moreover, the terminal departure policy could significantly improve the passenger waiting time. Waiting time can be decreased by 36% when almost all the buses depart the terminal on-time.

109. Using simulation model as a tool for analyzing bus service reliability and implementing improvement strategies

1. Moosavi, Seyed Mohammad Hossein; Ismail, Amiruddin; Yuen, Choon Wah
2. PLOS ONE
3. 2020

> Bus services naturally tend to be unstable and are not always capable of adhering to schedules without control strategies. Therefore, bus users and bus service providers face travel time variation and irregularity. After a comprehensive review of the literature, a significant gap was recognized in the field of public transportation reliability. According to literature, there is no consistency in reliability definition and indicators. Companies have their own definition of bus service reliability, and they mostly neglect the passengers' perspective of reliability. Therefore, four reliability indicators were selected in this study to fill the gap in the literature and cover both passengers' and operators' perceptions of reliability: waiting time and on-board crowding level from passengers' perspective, and headway regularity index at stops (HRIS) and bus bunching/big gap percentage from operators' perspective. The primary objective of this research is to improve the reliability of high frequency of bus service and simulation tools currently being used by the public transportation companies. Therefore, a simulation model of bus service was developed to study the strategies to alleviate it. Four different types of strategies were selected and implemented according to Route U32 (Kuala Lumpur) specifications. Model out-put showed that control strategies such as headwaybased dispatching could significantly improve headway regularity by almost 62% and the waiting time by 51% on average. Both holding strategies at key stops (previous and Prefol holding) have shown an almost similar impact on reliability indicators. Waiting time was reduced by 44% and 43% after the previous and Prefol Headway strategies were adopted, respectively. However, the implementation of the component of headway-based strategies at the terminal and key stops showed the best impact on reliability, in terms of passenger waiting time.

> Waiting time and excess waiting time were both significantly reduced by 52.86% and 81.44%, respectively. Nevertheless, the strategies did not show any significant positive effect on the level of crowding during morning peak hours.

110. Modeling Bus Bunching and Anti-bunching Control Accounting for Signal Control and Passenger Swapping Behavior

1. Xin, Qi; Fu, Rui; Yu, Shaowei; Ukkusuri, Satish, V; Jiang, Rui
2. JOURNAL OF PUBLIC TRANSPORTATION
3. 2021

> The conventional bus propagation modeling process has two main shortcomings: bus bunching and extra energy consumption caused by idling at signalized intersections and unexpected speed variation along the route. To overcome these problems simultaneously, an extended bus propagation model and anti-bunching control are proposed in this paper. To extend the time-based bus propagation model, the authors used a finite state machine and an intelligent driver model to establish a spatial-temporal based bus propagation model accounting for dynamic bus motion and passenger swapping behavior between bunched buses. To mitigate bus bunching and improve fuel economy in a connected environment, an anticipated average speed plan was used to improve headway regularity and reduce the chance of encountering a red signal. Then, predictive control accounting for state and control constraints was used to generate a smooth trajectory for connected buses to follow the commands given by anticipated average speed planning. This ensured that connected buses traversed signalized intersections and approached downstream stops efficiently. Simulations show that the proposed model can imitate passenger swapping behavior when bus bunching occurs, and the anti-bunching control can mitigate bus bunching and guide connected buses to traverse signalized intersections and reach downstream stops with less delay.

111. Improving Resilience of Bus Bunching Holding Strategy through a Rolling Horizon Approach

1. de Souza, Felipe; Teixeira Sebastiani, Mariana
2. JOURNAL OF TRANSPORTATION ENGINEERING PART A-SYSTEMS
3. 2021

> Providing public transportation with quality service is critical to attracting more passengers to the system. However, high-demand routes are prone to the so-called bus bunching-a tendency of buses to group as a consequence of variations in travel times and demands. Bus holding is applied to overcome this effect. In this study, we present a novel method for bus holding in which the control law is based only on the buses' position using a computationally efficient rolling horizon approach. The method uses similar inputs as linear control approaches while not increasing significantly the computational time. On the other hand, the method overcomes a key weakness of the linear control approach thanks to the explicit constraint handling that always ensures the control action effectiveness. Simulation experiments in a validation case and a model-specific for a bus rapid transit line in Curitiba, Brazil, showed a reduced holding time and improved resilience, delivering more than 20% reduction in delay time accounting for the on-board and station delays.

112. On the tradeoff between sensitivity and specificity in bus bunching prediction

1. Sun, Wenzhe; Schmocker, Jan-Dirk; Nakamura, Toshiyuki

2. JOURNAL OF INTELLIGENT TRANSPORTATION SYSTEMS
3. 2021

> Bus bunching resulting from initially small headway irregularities is a widely-known and studied problem. A variety of headway-prediction approaches, as well as corrective strategies, have been developed to identify and correct headway irregularity in real time. Instead of predicting an exact value for future headways, this study explores a probabilistic predictive methodology to forecast whether or not a bus will be bunched during its dwelling at a downstream stop, using a logistic regression model based on GPS records of buses at least k stops upstream to allow for sufficient time to possibly implement control strategies. A case study is conducted on a circular bus route in Kyoto City. Compared to two headway-based prediction approaches using linear regression and support vector machine, the superior performance of the proposed tool in detecting bunching is illustrated by Receiver Operator Characteristic (ROC) analysis. The high reliability in long-term prediction gives adequate time for operators to employ countermeasures. Besides, the proposed method provides operators with tradeoff options. We find that a bunching-averse operator can obtain 95% sensitivity, that is the ratio of correctly identified bunching events, at the cost of decreasing specificity, which is the ratio of correct non-bunching predictions over all events. This is true even if the prediction horizon is more than 10 stops.

113. The potential of real-time crowding information in reducing bus bunching under different network saturation levels

1. Drabicki, Arkadiusz; Cats, Oded; Kucharski, Rafal
2. 2021 7TH INTERNATIONAL CONFERENCE ON MODELS AND TECHNOLOGIES FOR INTELLIGENT TRANSPORTATION SYSTEMS (MT-ITS)
3. 2021

> Bus bunching is a well-known problem in public transport networks. It is characterized by a self-amplifying relationship between uneven distribution of rising passenger loads and deteriorating service regularity. The focus of this study is to analyse whether this negative feedback loop can be addressed by providing real-time crowding information (RTCI) on next vehicle departures at stops. We integrate a departure choice model based on stated-preference analysis of passengers' willingness to wait with RTCI. A proof-of-concept application to a toy-network model shows that this prevents further progression of bunching effects in certain demand conditions. The RTCI usage reveals substantial benefits - in terms of relative reductions in on-board (over)crowding, headway deviations, as well as mitigated denial-of-boarding risk - in moderately saturated network. These gains may diminish though as high overcrowding eventually emerges in PT network. Nevertheless, our findings indicate that RTCI has the potential to improve travel experience and service utilisation efficiency, even without resorting to supply-side control strategies.

114. Analysis and Simulation of Intervention Strategies against Bus Bunching by means of an Empirical Agent-Based Model

1. Quek, Wei Liang; Chung, Ning Ning; Saw, Vee-Liem; Chew, Lock Yue
2. COMPLEXITY
3. 2021

> In this paper, we propose an empirically based Monte Carlo bus-network (EMB) model as a test bed to simulate intervention strategies to overcome the inefficiencies of bus bunching. The EMB model is an agent-based model which utilizes the positional and temporal data of the buses obtained from the Global Positioning System (GPS) to constitute (1) a set of empirical velocity distributions of the buses and (2) a set of exponential distributions of interarrival time of passengers at the bus stops. Monte Carlo sampling is then performed on these two derived probability distributions to yield the stochastic dynamics of both the buses' motion and passengers' arrival. Our EMB model is generic and can be applied to any real-world bus network system. In particular, we have validated the model against the Nanyang Technological University's Shuttle Bus System by demonstrating its accuracy in capturing the bunching dynamics of the shuttle buses. Furthermore, we have analyzed the efficacy of three intervention strategies: holding, no-boarding, and centralized-pulsing, against bus bunching by incorporating the rule set of these strategies into the model. Under the scenario where the buses have the same velocity, we found that all three strategies improve both the waiting and travelling times of the commuters. However, when the buses have different velocities, only the centralized-pulsing scheme consistently outperforms the control scenario where the buses periodically bunch together.

115. Optimal holding time calculation algorithm to improve the reliability of high frequency bus route considering the bus capacity constraint

1. Liang, Shidong; He, Shengxue; Zhang, Hu; Ma, Minghui
2. RELIABILITY ENGINEERING & SYSTEM SAFETY
3. 2021

> The self-equalizing bus headway control method, as a type of headway-based control method, has been proved to resist bus bunching effectively. This control method is suitable for use in real-time transit operations owing to its simplicity in the formulation and solution. However, previous studies paid more attention on the demonstration that the bus headways can converge under variable conditions, without considering the bus capacity constraint. In addition, when the bus capacity constraint is considered, the optimal holding time calculation becomes a nonlinear problem instead of a simple linear problem. Therefore, in this study, a more precise and comprehensive model is proposed to describe the bus operation process. An optimal holding time calculation algorithm is proposed to solve the nonlinear optimization problem by transforming it into an one-dimensional line search problem. The proposed model was validated through numerical tests. In the traditional analyses, bus bunching will worsen if no additional control method is applied to the bus system. However, the present study indicates that bus bunching will be mitigated to some extent by the public transit system itself without external control at relatively high traffic demand level.

116. Robust optimal predictive control for real-time bus regulation strategy with passenger demand uncertainties in urban rapid transit

1. Ma, Qianqian; Li, Shukai; Zhang, Huiming; Yuan, Yin; Yang, Lixing
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2021

> The bus is inevitably affected by various factors during the trip, which causes that the phenomenon of bus bunching often occurs. This paper proposed a nonlinear optimal control model with passenger demand and disturbance uncertainties for the real-time bus regulation in urban rapid transit. The aim of this model is to assure the stability of bus headway in the line, reduce passengers' waiting time and

> improve bus service level. Considering the system uncertainties and the real-time control requirement of bus regulation, a robust optimal predictive control algorithm is put forward to generate the real-time optimal bus regulation strategy based on updated delay feedback of buses by a rolling horizon strategy. Simultaneously, by using continuous interval number to describe the uncertain parameters, the robust counterpart of the formulated robust optimization model is obtained using the duality theory, which is further converted to a mixed integer convex quadratic programming problem by a linearization method, which can be easily solved to obtain the robust solution with a good performance for any value of uncertain parameters. Finally, some numerical experiments are conducted to verify the validity of the presented optimization model in improving the stability of the bus headway.

117. An Integrated Bus Holding and Speed Adjusting Strategy Considering Passenger's Waiting Time Perceptions

1. Chen, Weiya; Zhang, Hengpeng; Chen, Chunxiao; Wei, Xiaofan
2. SUSTAINABILITY
3. 2021

> To solve the problems of bus bunching and large gaps, this study combines bus holding and speed adjusting to alleviate them respectively considering the characteristics of passenger's perceived waiting time. The difference between passenger's perceived waiting time at stops and actual time is described quantitatively through the expected waiting time of passengers. Bus holding based on a threshold method is implemented at any stops for bunching buses, and speed adjusting based on a Markovian decision model is implemented at limited stops for lagging buses. Simulations based on real data of a bus route show that the integrated control strategy is able to improve the service reliability and to decrease passengers' perceived waiting time at stops. Several insights have been uncovered through performance analysis: (1) The increase of holding control strength results in improvement of the headway regularity, and leads to a greater perceived waiting time though; (2) Compared to traveling freely, suitable speed guidance will not slow down the average cruising speed in the trip; (3) The scale of passenger demand and through passengers are the two key factors influencing whether a stop should be selected as a speed-adjusting control point.

118. Does the measured performance of bus operators depend on the index chosen to assess reliability in contracts? An analysis of bus headway variability

1. Godachevich, Javiera; Tirachini, Alejandro
2. RESEARCH IN TRANSPORTATION ECONOMICS
3. 2021

> The choice of performance indicators in bus contracts is a complex problem for public transport regulators and financial incentives to provide a reliable service have been designed by several agencies. We study the issue of bus headway variability, focusing on headway variability at bus dispatching, which is a very relevant issue that has not been properly analysed in existing studies, despite the considerable influence of irregular dispatching on bus bunching. We identify the variables that are statistically significant in explaining bus headway variability at the beginning of routes, using large GPS and smartcard databases of all bus routes in Santiago, Chile. Three measures of headway variability are used: standard deviation, modified index per observation and an ad-hoc measure included in the Santiago bus contracts, called 'minutes of incidence'. Significant variables to explain headway variability

> are bus frequency, number of bus services per terminal, distance from the bus depot to the first stop, route length, bus demand and operating speed. The measured performance of each bus operator is different depending on the headway variability indicator used, which points to the relevance of choosing an appropriate index of service reliability as a financial incentive in contracts. Implications for service planning are discussed.

119. Mitigating Bunching With Bus-Following Models and Bus-to-Bus Cooperation

1. Ampountolas, Konstantinos; Kring, Malcolm
2. IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS
3. 2021

> Bus bunching is an instability problem where buses operating on high-frequency public transport lines arrive at stops in bunches. This work unveils that bus-following models can be used to design bus-to-bus cooperative control strategies and mitigate bunching. The use of bus-following models avoids the explicit modelling of bus-stops, which would render the resulting problem discrete, with events occurring at arbitrary time intervals. In a follow-the-leader two-bus system, bus-to-bus communication allows the driver of the following bus to observe (from a remote distance) the position and speed of the leading bus operating in the same transport line. The information transmitted from the leader is then used to control the speed of the follower to eliminate bunching. A platoon of buses operating in the same transit line can be then controlled as leader-follower dyads. In this context, we propose practical control laws to regulate speeds, which would lead to bunching cure. A combined state estimation and remote control scheme is developed to capture the effect of disturbances and randomness in passenger arrivals. To investigate the performance of the developed schemes the 9-km 1-California line in San Francisco with about 50 arbitrary spaced bus stops is used. Simulations with empirical passenger data are carried out. Results show bunching avoidance and improvements in terms of schedule reliability of bus services and delays. The proposed control is robust, scalable in terms of transit network size, and thus easy to deploy by transit agencies to improve communication and guidance to drivers, and reduce costs.

120. Operation of transit corridors served by two routes: Physical design, synchronization, and control strategies

1. Estrada, Miquel; Mension, Josep; Salicru, Miquel
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2021

> Many transit network layouts require the operation of multiple routes along a common transit segment in the busiest area of the city. At some points, these routes branch out to provide spatial coverage to the city periphery. These schemes allow more efficient deployment of resources at the expense of introducing more complexity into the system operation. This study aims to determine the effect of the branched layout of a corridor, demand distribution and traffic lights on the total cost of the system as well as its service regularity. The transit corridor is operated by buses, although it can be generalized for other transit modes. An operational model to estimate the travel and waiting time of users and the performance of buses on each route segment is developed. The model considers the stochastic effect of the passenger arrivals at stops and vehicle acceleration-deceleration rates. An optimization procedure to determine the optimal headway and relative synchronization of routes, which minimizes the total cost incurred by transit agencies and users or the headway variations in the common route

> segment, is introduced. Furthermore, a performance evaluation of bus control strategies based on a combination of holding points and green extensions at traffic signals in the H10 cross-town corridor of Barcelona's new bus network is presented.

121. Improving service regularity for high-frequency bus services with rescheduling and bus holding

1. Gkiotsalitis, Konstantinos
2. JOURNAL OF TRAFFIC AND TRANSPORTATION ENGINEERING-ENGLISH EDITION
3. 2021

> In high-frequency bus services, maintaining the service regularity is a critical issue. The service regularityis directly related to the excessive waiting times (EWT) of passengers atbus stops. In a regular service, the EWT isminimized resulting in even headways between consecutive buses of the same line. In this study, we propose the combined use of rescheduling and busholding to improve passengers' excessive waiting times. We model the dynamic rescheduling and bus holding problem as an integer nonlinear program (INLP) and we prove its NP-hardness. Our model considers the constraints of the original timetable e an issue that is usually neglected from most dynamic control methods. Given the NP-hardness of our mathematical program, we introduce a problem-specific heuristic to explore efficiently the solution space. The convergence rate of the proposed heuristic is tested against other solution methods, including simulated annealing with linear cooling, hill climbing and branch and bound with multi-start sequential quadratic programming. In addition, simulations with the use of actual operational data from a major bus operator in Asia Pacific demonstrate an up to 35% potential EWT improvement for aminor increase of 6% to the travel times of onboard passengers. (C) 2021 Periodical Offices of Chang'an University. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd.

122. Providing real-time bus crowding information for passengers: A novel policy to promote high-frequency transit performance

1. Wang, Pengfei; Chen, Xuewu; Zheng, Yue; Cheng, Long; Wang, Yinhai; Lei, Da
2. TRANSPORTATION RESEARCH PART A-POLICY AND PRACTICE
3. 2021

> Bus bunching is of particular concern and undesirable for both operators and passengers in highfrequency transit. In contrast to existing control methods, this paper proposes a novel control policy, namely, providing real-time bus crowding information (BCI) for passengers. It is believed that passengers would spontaneously distribute more evenly among buses and help to prevent bus bunching with the provision of BCI accompanying arrival time information due to the following mechanism. A proportion of passengers would be likely to wait a few more minutes for the next bus when the current bus is crowded and the next bus is more comfortable, and the boarding times of these passengers would make the next bus dwell longer and increase its headway from the previous bus. We formulate bus motion models incorporating passenger boarding choice under BCI to realize the policy in simulation experiments. The results demonstrate that the policy can reduce operation instability by approximately 20% in terms of bus headway and single-trip time. In addition, this policy can significantly reduce the in-vehicle crowdedness experienced by passengers by up to 25% at the cost of small increases in the mean journey time in some cases. The simulation experiments on a holding-controlled route also indicate that the proposed policy is able to coordinate with holding well.

> A sensitivity analysis further confirms that the policy's performance is robust even if the passengers have low inclinations to choose the next bus. The policy of providing BCI in this paper is especially effective for bus routes with high passenger demand and may have great application potential in practice.

123. A self-organizing policy for vehicle dispatching in public transit systems with multiple lines

1. van Lieshout, Rolf N.; Bouman, Paul C.; van den Akker, Marjan; Huisman, Dennis
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2021

> In this paper, we propose and analyze an online, decentralized policy for dispatching vehicles in a multi-line public transit system. In the policy, vehicles arriving at a terminal station are assigned to the lines starting at the station in a round-robin fashion. Departure times are selected to minimize deviations from a certain target headway. We prove that this policy is self-organizing: given that there is a sufficient number of available vehicles, a timetable spontaneously emerges that meets the target headway of every line. Moreover, in case one of the vehicles breaks down, the remaining vehicles automatically redistribute over the network to re-establish such a timetable. We present both theoretical and numerical results on the time until a stable state is reached and on how quickly the system recovers after the breakdown of a vehicle. Experiments on three real-world transit systems show that our policy performs well, even if not all assumptions required for the theoretical analysis are met: if there are enough vehicles, the realized headways are typically close to the target headways. These promising results suggest that our self-organizing policy could be useful in situations where centralized dispatching is impractical or simply impossible due to an abundance of disruptions or the absence of information systems.

124. Bus Arrival Time Prediction Model Based on Multi-Resource Data

1. Luo, Xubin; Fu, Hui; Han, Shuang
2. CICTP 2021: ADVANCED TRANSPORTATION, ENHANCED CONNECTION
3. 2021

> To predict bus arrival time at each stop with complex real-time traffic factors changing on the road, this paper proposes a dynamic arrival time prediction model for buses, using a combination of real-time taxi and bus datasets, with a kernel algorithm of statistical methods or neural networks to model the properties of dynamic road circumstances. This is a rolling prediction method, which uses the prediction result of previous step as the input features of the next prediction, to predict all bus arrival times of future stops. The result shows that the proposed dynamic model is applicable for bus arrival time prediction, where datasets with taxi are more accurate than without it. The possible bus bunching can be captured by checking the predicted time headway between buses from the same bus line, and long-time delay in terminals can also be predicted and eliminated by rescheduling departure time of targeted buses.

125. Bus arrival time prediction and reliability analysis: An experimental comparison of functional data analysis and Bayesian support vector regression

1. Huang, Y. P.; Chen, C.; Su, Z. C.; Chen, T. S.; Sumalee, A.; Pan, T. L.; Zhong, R. X.
2. APPLIED SOFT COMPUTING

3. 2021

> To maintain the stability and punctuality of bus systems, an accurate forecast of arrival time is essential to devise control strategies to prevent bus bunching especially under congested traffic conditions. Transit agencies provide travelers with accurate and reliable bus arrival times to downstream stations to improve transit service quality so as to attract more transit riders. Varieties of approaches have been dedicated to providing high prediction accuracy while the measure of the associated uncertainty is ignored. Noting that the quantification of uncertainty is vital for robust performance, this paper proposes data-driven approaches based on the Functional Data Analysis (FDA) and Bayesian Support Vector Regression (BSVR) for short-term bus travel time prediction while anticipating various uncertainties. To capture spatial-temporal dynamic traffic conditions along the route so as to increase the accuracy of the journey time prediction and to capture the skewness in journey time distribution, a probabilistic nested delay operator is adopted. Journey time reliability analysis is then conducted using the skewness of dynamic journey time distribution. An empirical study is carried out by fusing the bus transit date of No. 261 bus route and Floating Car Data (FCD) in Guangzhou. The proposed FDA and BSVR methods applied in conjunction with the probabilistic nested delay operator turn out to be highly competitive when performing forecasts under various traffic conditions. Comparative studies indicate that FDA provides more accurate prediction results and tends to anticipate uncertainties in journey time distribution more effectively.

126. Dynamic Bus Dispatch Policies

1. Koppisetti, M. Venkateswararao; Kavitha, Veeraruna
2. NETWORK GAMES, CONTROL AND OPTIMIZATION, NETGCOOP 2020
3. 2021

> The time gap between two successive buses is called headway in transport systems. In moderate/high frequency routes, with moderate/small headways, the random perturbations (traffic conditions, passenger arrivals, etc.), can alter the headway along the route significantly which possibly leads to bunching of buses. Two or more (successive) buses may start travelling together. Bus bunching results in inefficient and unreliable bus service and is one of the critical problems faced by bus agencies. Thus it is imperative to reduce the bunching possibilities (probability). Another important aspect is the expected time that a typical passenger has to wait before the arrival of its bus. If one increases the headway, the bunching chances might reduce, however, may significantly increase the passenger waiting times. We precisely study this inherent trade-off and derive a bus schedule optimal for a joint cost related to all the trips, which is a weighted combination of the two performance measures. We consider a system with Markovian travel times, fluid passenger arrivals and derive dynamic headways which control the bus frequency based on the observed system state. The observation is a delayed information of the time gaps between successive bus arrivals at various stops, corresponding to two earlier (previous to previous) trips. We solve the relevant dynamic programming equations to obtain near-optimal policies, and the approximation improves as the load factor reduces. The near-optimal policy turns out to be linear in previous headway and the (earlier) bus-inter-arrival times. Using Monte Carlo based simulations, we demonstrate that the proposed dynamic policies significantly improve (both) the performance measures, in comparison with the previously proposed partial dynamic policies that only depend upon the headways of the previous trips.

127. A Decision Tree Ensemble Model for Predicting Bus Bunching

1. Santos, Veruska Borges; Pires, Carlos Eduardo S.; Nascimento, Dimas Cassimiro; de Queiroz, Andreza Raquel M.
2. COMPUTER JOURNAL
3. 2022

> Travel delays and bus overcrowding are some of the daily dissatisfactions of public transportation users. These problems may be caused by bus bunching, an event that occurs when two or more buses are running the same route together, i.e. out of schedule. Due to the stochastic nature of the traffic, a static schedule is not effective to avoid the occurrence of these events; thus, preventive actions are necessary to improve the reliability of the public transportation system. In this context, we propose a decision tree ensemble model to predict bus bunching. We use an ensemble of Random Forest, eXtreme Gradient Boosting and Categorical Boosting models applied to Global Positioning System, General Transit Feed Specification, weather and traffic situation data. The efficacy of the proposed model has been demonstrated using real data sets and has been compared with four baselines: Linear Regression, Logistic Regression, Support Vector Machine and Relevance Vector Machine. According to the results, the proposed model can achieve an efficacy between 74 and 80% and can be used to predict bus bunching in real time up to 10 stops before its occurrence.

128. A short-turning strategy to alleviate bus bunching

1. Tian, Shengnan; Li, Xiang; Liu, Jiaming; Ma, Hongguang; Yu, Haitao
2. JOURNAL OF AMBIENT INTELLIGENCE AND HUMANIZED COMPUTING
3. 2022

> Some stops on busy bus lines regularly suffer from bus bunching, which refers to a bus arriving with a little headway to its predecessor. This phenomenon increases scheduling difficulties and has a negative impact on the passenger experience due to unreasonable scheduling. The conventional holding strategy aims to alleviate this problem by holding buses at control points. However, the holding strategy has the drawbacks of creating large deviations from the original schedule and prolonging passenger waiting time when confronted with traffic congestion. This study proposes an innovative short-turning strategy to alleviate bus bunching by the deliberate conversion of a few regular trips to short-turning trips. A nonlinear optimisation model is developed by rescheduling a set of trips using the short-turning strategy to minimise schedule deviation from the original schedule. The nonlinear short-turning model is then converted into a linear form that is solvable by CPLEX. Based on real data from the Yuntong 111 bus line in Beijing, China, the proposed short-turning strategy is deployed in a simulation experiment. The results show that the short-turning strategy is superior at alleviating bus bunching than the alternatives of no control strategy and the holding strategy. Compared with no control strategy, the short-turning strategy can achieve a more than 43.44% reduction in schedule deviation and significantly reduce total passenger waiting time by up to 8.99%.

129. Travel Time Reliability Analysis Considering Bus Bunching: A Case Study in Xi'an, China

1. Zhang, Yanan; Xu, Hongke; Lu, Qing-Chang; Fan, Xiaohui
2. SUSTAINABILITY
3. 2022

> Bus bunching occurring at stops has an unstable impact on bus travel time. In order to evaluate urban bus travel time effectively, the travel time reliability (TTR) addressing bus bunching is analyzed. This

> paper focuses on the delayed time caused by bus bunching in the dwelling process at bus stops and uses the coefficient of variation of time headway to evaluate the degree of bus bunching. Moreover, the travel time deviation (TTD) indicator and travel time on-time accuracy (OTA) model are proposed to evaluate the bus TTR. The proposed model is used to analyze 113 runs of a bus route in Xi'an city, China. Real-time GPS data are used to analyze the operation of each run from the origin to the destination stops. The results show that 74.34% of the runs are delayed. When the value of TTD is higher than |0.1|, 64.2% of runs are delayed with bus bunching. Based on the measuring of OTA in two situations, the value of TTR considering bus bunching is reduced by 20%. In addition, the number of stopping routes at peak periods has a significant impact on the occurrence of bus bunching. The research results would have practical implications for the operation and management of buses.

130. Does bus bunching happen inevitably: The counteraction between link and stop headway deviations?

1. Chen, Guojun; Zhang, Shuyang; Lo, Hong K.; Liu, Haode
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2022

> Bus headway deviations are the major causes of bus bunching, which is detrimental to bus service reliability and leads to excessive waiting time for passengers. Generally, it is believed that bus bunching is an inevitable result once a service disturbance occurs, as long as the route is long enough. However, in this study, it goes as low as 5% of all trips from the empirical data, con-tradicting the expectation in theory. This study explores the underlying reasons for this contra-diction based on empirical data from two representative bus routes in China. The results show that headway deviations on links and at stops mostly counteract with each other, constraining the occurrence of bus bunching. Under this counteraction effect, the path headway deviations remain within a stable range, normally bounded by the planned headway. It indicates that the bus system has a self-repair ability to resist headway disruptions, which explains why bus bunching happens at a considerably lower frequency in practice than in theory. We further discuss how the coun-teraction effect works. The insights gained from this study can shed light on preventing bus bunching and generating new ways to recover bus service regularity after a headway disruption. If we can adequately adjust the control methods to make the link and stop headway deviations counteract with each other, the bus system can automatically mitigate the headway deviations.

131. A Real-Time Control Strategy for Bus Operation to Alleviate Bus Bunching

1. Xue, Yunqiang; Zhong, Meng; Xue, Luowei; Tu, Haokai; Tan, Caifeng; Kong, Qifang; Guan, Hongzhi
2. SUSTAINABILITY
3. 2022

> In order to alleviate bus bunching and improve the balance and punctuality rate of bus operation, a single-line real-time control strategy based on Intelligent Transportation System (ITS) was proposed. The strategy took three measures: controlling the cruising speed, dwell time, and the bus load rate to improve the stability of bus operations and to ensure its running speed. At the same time, the proposed strategy was compared with the literature on the traditional single-point control strategy based on timetable (S1 for short) and the multi-point control strategy based on time headway (S2 for short). Finally, the No. 245 bus line in Nanchang City, China, was selected as a case. It was modeled and simulated by Python programming software, and the control effects of the three control strategies

> were analyzed. Compared with the uncontrolled bus operations, the simulation results show that: under the control of S1, the bus operation stability is improved, but the bus operation efficiency is reduced; under the control of S2, the problem of S1 operation efficiency reduction can be solved, and the operation stability can be improved at the same time to achieve the effect of preventing bunching. For the real-time control strategy (S3 for short), the average bus travel time is the smallest, the distance between the buses is maintained the best, and the running stability is also the best, which avoids the bus bunching to the greatest extent. Among them, the average travel time is reduced by about 34% compared with the second strategy. This study provides a theoretical basis and strategy reference for bus operators to ensure balanced bus operation.

132. Identifying Spatial-Temporal Characteristics and Significant Factors of Bus Bunching Based on an eGA and DT Model

1. Yan, Min; Xie, Binglei; Xu, Gangyan
2. APPLIED SCIENCES-BASEL
3. 2022

> Bus bunching is a common phenomenon caused by irregular bus headway, which increases the passenger waiting time, makes the passenger capacity uneven, and severely reduces the reliability of bus service. This paper clarified the process of bus bunching formation, analyzed the variation characteristics of bus bunching in a single day, in different types of periods, and at different bus stops, then concluded twelve potential factors. A hybrid model integrating a genetic algorithm with elitist preservation strategy (eGA) and decision tree (DT) was proposed. The eGA part constructs the model framework and transforms the factor identification into a problem of selecting the fittest individual from the population, while the DT part evaluates the fitness. Model verification and comparison were conducted based on real automatic vehicle location (AVL) data in Shenzhen, China. The results showed that the proposed eGA-DT model outperformed other frequently used single DT and extra tree (ET) models with at least a 20% reduction in MAE under different bus routes, periods, and bus stops. Six factors, including the sequence of the bus stop, the headway and dwell time at the previous bus stop, the travel time between bus stops, etc., were identified to have a significant effect on bus bunching, which is of great value for feature selection to improve the accuracy and efficiency of bus bunching prediction and real-time bus dispatching.

133. Bus bunching from a stop-based perspective: insights from visual analytics

1. Tsoi, Ka Ho; Loo, Becky P. Y.
2. PROCEEDINGS OF THE INSTITUTION OF CIVIL ENGINEERS-MUNICIPAL ENGINEER
3. 2022

> Bus bunching can deteriorate bus service quality and jeopardise the effectiveness of public transit in promoting sustainable urban transport. This study applies artificial intelligence (AI) techniques in visual analytics to examine the spatiotemporal characteristics of bus bunching from a stop-based perspective. A total of 25 405 real-time traffic images were extracted and analysed from 11 bus stops in Hong Kong in August 2019 (7am-7pm, Tuesdays-Thursdays). An image classification model was developed with an overall accuracy of 85%. Three distinct groups were identified based on the spatiotemporal characteristics of bus bunching at different bus stops. They are (a) systematic peak hour, (b) minor and intermittent and (c) random bus bunching. Specific traffic conditions in terms of traffic speed, traffic composition and bus occupancy rate are highly associated with the onset of bus bunching. Overall

> traditional bus management tactics, such as schedule synchronisation and headways control, need to be supplemented by stop-based strategies that consider the temporal profiles of bus bunching and associated traffic conditions on road.

134. A novel control strategy in mitigating bus bunching: Utilizing real-time information

1. Zhou, Chang; Tian, Qiong; Wang, David Z. W.
2. TRANSPORT POLICY
3. 2022

> A variety of control mechanisms have been recommended to concentrate on the issue of bus bunching. However, the majority of existing measures focus on controlling the bus operation directly from the operator's perspective. This study, nevertheless, presents a novel control technique by providing passengers with real-time wait time information and degrees of in-vehicle congestion. Specifically, passengers are expected to use the given information to calculate the overall travel cost and, therefore, make decisions on whether boarding on the arriving bus or waiting for the next buses. In this way, bus service operators would reduce bus bunching by adjusting passengers' boarding choice behavior rather than controlling the bus vehicles directly. We propose a bus traffic propagation model to simulate the bus movements, through which several system performance metrics, such as the shortest vehicle spacing distribution and the average ridership per bus vehicle at each stop, can be evaluated for different bus bunching control measures. The numerical results show that providing in-vehicle congestion information is as effective as the schedule-based and headway-based control methods in achieving mitigation of bus bunching. Passengers on long trips are more inclined to wait for a few more shifts for a bus that is not very crowded. This study proposes a novel control strategy by offering passengers real-time information to serve as a supplement, never a substitute, to the existing control measures in mitigating bus bunching problems.

135. Synchronising Bus Bunching to the Spikes in Service Demand Reduces Commuters' Waiting Time

1. Vismara, Luca; Saw, Vee-Liem; Chew, Lock Yue
2. COMPLEXITY
3. 2022

> Bus bunching is ostensibly regarded as a detrimental phenomenon in bus systems. We study a bus loop with two bus stops, one regular bus stop and one spike bus stop, where bunched buses can outperform staggered buses. The spike bus stop models a bus stop connected to a train or metro service, where passengers arrive in groups at periodic intervals (spikes). We introduce the configuration of synchronised bunched buses, where bunched buses wait for the spike in demand. For a wide range of parameters, synchronised bunched buses outperform perfectly staggered buses in terms of minimising the waiting time of commuters. We present an analytical formulation of the average waiting time in the case of bunched buses, synchronised bunched buses, and perfectly staggered buses with the consideration of different passenger demands, number of buses, and bus capacity. We demonstrate the validity of our analytical results through an agent-based simulation of the bus loop system.

136. Zero bunching solution for a local public transport system with multiple-origins bus operation

1. Sajikumar, S.; Bijulal, D.
2. PUBLIC TRANSPORT
3. 2022

> Bus bunching in public transport is the concentration of similar buses having different schedules to a common time point. The reason for this phenomenon is variations existing in the bus operation as earliness and lateness. Bus bunching has the consequence of reduced service reliability concerning both passengers and operators. A zero bunching state is vital for enhancing the usage of public transport where the buses operate with utmost schedule adherence. Two generally adopted strategies for solving bus bunching are a schedule-based strategy which provides slack time in a timetable to address late running and fixed departure time for the early operations, and a headway-based strategy that maintains headway between buses. Bus bunching due to multiple origins is a special case in which common tactics cannot effectively control a bunching tendency that arises at the entry point. The operation schedules of multiple origins must be so designed that a state of zero bus bunching can be ensured while buses from different origins reach the entry points. This article presents a model of a multiple-origins public transport network as a combination of origins, routes and entry points, developed in the search for achieving a zero bunching state in the operation beyond an entry point. The origins are modelled based on the entry-point variables. The routes are modelled based on the running time, departure time, arrival time, and dwell time. The entry points are modelled based on route and entry-point variables. Redesigning route schedules based on the entry-point characteristics and an appropriate slack time implementation are proposed and observed to be suitable for overcoming bunching in a multiple-origins bus operation.

137. Bilevel Optimization for Bunching Mitigation and Eco-Driving of Electric Bus Lines

1. Lacombe, Remi; Gros, Sebastien; Murgovski, Nikolce; Kulcsar, Balazs
2. IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS
3. 2022

> The problems of bus bunching mitigation and the energy management of groups of vehicles have traditionally been treated separately in the literature and been formulated in two different frameworks. The present work bridges this gap by formulating the optimal control problem of the bus line eco-driving and regularity control as a smooth, multi-objective nonlinear program. Since this nonlinear program has only a few coupling variables, it is shown how it can be solved in parallel aboard each bus, such that only a marginal amount of computations need to be carried out centrally. This procedure leverages the structure of the bus line by enabling parallel computations and reducing the communication loads between the buses, which makes the problem resolution scalable in terms of the number of buses. Closed-loop control is then achieved by embedding this procedure in a model predictive control. Stochastic simulations based on real passengers and travel times data are realized for several scenarios with different levels of bunching for a line of electric buses. Our method achieves fast recoveries to regular headways as well as energy savings of up to 9.3% when compared with traditional holding or speed control baselines.

138. Scheduling Synchronization for Overlapping Segments in Bus Lines: Speed Control and Green Extension Strategies

1. Zhao, Hu; Feng, Shumin; Ci, Yusheng; Xin, Mengwei; Huang, Qiuju
2. JOURNAL OF ADVANCED TRANSPORTATION

3. 2022

> Overlapping bus lines are ubiquitous in bus networks, particularly in metropolitan areas. The overlapping of bus lines can provide convenience for passengers who wish to transfer. However, it also tends to cause bus bunching at overlapping segment stops. Moreover, overlapping of bus lines introduces additional complexity to the operation of bus systems. This study aimed to dispatch bus vehicles entering overlapping segments dynamically by adopting speed control and green light extension strategies. This ensures that transferring passengers experience less transfer waiting time and reduced bus bunching at overlapping segments. The proposed model considers environmental constraints on vehicle speed and the stochastic factors of passenger arrivals at a stop. Synchronization is maximized by controlling the speed of vehicles along a roadway and determining whether a green light extension strategy is enabled. The effectiveness of the proposed model was verified by applying it to a real overlapping segment in Harbin, China. The results demonstrate that the proposed model can more than double the opportunity for synchronization in overlapping segments while reducing bus bunching at the stops in overlapping segments.

139. A distributed deep reinforcement learning-based integrated dynamic bus control system in a connected environment

1. Shi, Haotian; Nie, Qinghui; Fu, Sicheng; Wang, Xin; Zhou, Yang; Ran, Bin
2. COMPUTER-AIDED CIVIL AND INFRASTRUCTURE ENGINEERING
3. 2022

> The bus bunching problem caused by the uncertain interstation travel time and passenger demand rate is a critical issue that impairs transit efficiency. Most current bus control studies focus on single or combined strategies while ignoring the bus system's real-time environmental information. This paper proposed a distributed deep reinforcement learning (DRL)-based generic bus dynamic control method to solve the bus bunching problem by maintaining the schedule adherence, headway regularity, and achieving the consensus in the multiagent system. This study built a bus system that utilizes the bus historical and traffic information by incorporating these characteristics into the environment. After that, a distributed DRL-based bus dynamic control strategy is developed based on the bus system, enabling each bus to adjust its motion by any generic method utilizing the weighted downstream buses' information. Regarding the training process, a distributed proximal policy optimization algorithm is adopted for improving the converging performance. Simulated experiments are conducted to verify the control performance, robustness, feasibility, resilience, and generalization capability, which shows that our strategy can significantly reduce the schedule and headway deviations, prevent the accumulation of deviation downstream, and avoid bus bunching.

140. Headway variability in public transport: a review of metrics, determinants, effects for quality of service and control strategies

1. Tirachini, Alejandro; Godachevich, Javiera; Cats, Oded; Munoz, Juan Carlos; Soza-Parra, Jaime
2. TRANSPORT REVIEWS
3. 2022

> The most relevant issues related to headway variability in public transport planning, operations and quality of service are reviewed in this paper. We discuss the causes and consequences of headway variability, the alternative metrics that have been proposed to measure it, the preventive and reactive

> strategies to control headway variability in both research and practice, including the role of drivers and of present and future technology, and how service provision contracts might deal with headway variability through metrics and financial incentives. The most influential elements that explain headway variability along a route are the irregularity at which vehicles are dispatched, the scheduled frequency, the distance travelled or route length, the passenger demand and associated dwell times, and the number of stops. We conclude that there is a large gap between the state-of-the-art and the state-of-practice in terms of identification of headway variability issues, as well as in the development of mitigation and control measures. It is therefore paramount that future research will contribute to closing this gap by addressing organisational, contractual and technological barriers in the implementation of measures aimed at mitigating headway variability in public transport services.

141. Bus Predictive-Control Method considering the Impact of Traffic Lights

1. Li, Maosheng; Li, Yao
2. JOURNAL OF ADVANCED TRANSPORTATION
3. 2022

> Amid the COVID-19 pandemic, many travelers have switched from public transit to other modes. How to maintain the stability and service quality of the bus system under regular pandemic prevention and control, so as to maintain the attractiveness of the bus, is an important research direction. Predicting operation states and adopting appropriate control measures for running buses are effective means of improving the bus system's schedule reliability and service quality. Focusing on the impacts of intersection traffic lights on the link's travel time durations, we establish a probabilistic prediction model for bus headways, classifying the bus headways into three states: bunching, stable, and big gap states. Based on the prediction of bus headways, the most suitable control strategy is selected by the proposed method from the plan set, such as holding control, speed-adjusting control, and stop-skipping control to minimize the bus headway deviation. Simulation experiments were employed to verify the effectiveness of the proposed method. Compared with the no-control situation, the expected headway variation, average passenger waiting time, and bus bunching frequency for 100 simulations by the proposed method are reduced by 77.73%, 41.66%, and 87.11%, respectively. Compared with some control methods without prediction, the proposed method is more robust, maintains good control performance, and reduces bus bunching despite significant variations in environmental parameters. In addition, the model still performs well when considering the execution errors of bus drivers.

142. A Dynamic Holding Approach to Stabilizing a Bus Line Based on the Q-Learning Algorithm with Multistage Look-Ahead

1. He, Sheng-Xue; He, Jian-Jia; Liang, Shi-Dong; Dong, June Qiong; Yuan, Peng-Cheng
2. TRANSPORTATION SCIENCE
3. 2022

> The unreliable service and the unstable operation of a high-frequency bus line are shown as bus bunching and the uneven distribution of headways along the bus line. Although many control strategies, such as the static and dynamic holding strategies, have been proposed to solve the above problems, many of them take on some oversimplified assumptions about the real bus line operation. So it is hard for them to continuously adapt to the evolving complex system. In view of this dynamic setting, we present an adaptive holding method that combines the classic approximate dynamic

programming (ADP) with the multistage look-ahead mechanism. The holding time, the only control means used in this study, will be determined by estimating its impact on the operation stability of the bus line system in the remaining observation period. The multistage look-ahead mechanism introduced into the classic Q-learning algorithm of the ADP model makes it easy that the algorithm gets through its earlier unstable phase more quickly and easily. During the implementation of the new holding approach, the past experiences of holding operations can be cumulated effectively into an artificial neural network used to approximate the unavailable Q-factor. The use of a detailed simulation system in the new approach makes it possible to take into account most of the possible causes of instability. The numerical experiments show that the new holding approach can stabilize the system by producing evenly distributed headway and removing bus bunching thoroughly. Compared with the terminal station holding strategies, the new method brings a more reliable bus line with shorter wait

143. Comparison of Two Algorithms for Multiline Bus Dynamic Dispatching

1. Liu, Yingxin; Luo, Xinggang; Cheng, Shengping; Yu, Yang; Tang, Jiafu; Shang, Xuanzhu
2. DISCRETE DYNAMICS IN NATURE AND SOCIETY
3. 2022

Dynamic bus scheduling refers to adjusting the departure time according to the latest time-varying information or adjusting bus speed in the process of operation. These control strategies can prevent bus bunching and alleviate traffic pressure. The paper studies the multiline bus dynamic scheduling with consideration of departure time and speed meanwhile. The hyperheuristic algorithm is proposed, and low-level heuristics (LLH) operators are designed. The simulation experiment is performed for the passenger flow distribution of different strengths and types of different scenarios. By comparing the experimental results of genetic algorithm (GA) and hyperheuristic algorithm in solving different scenarios, the results show that in smooth, increasing, decreasing, and multiconvex passenger flow mode, the performance of the hyperheuristic algorithm is higher than that of GA. The promotion rate reaches 18 similar to 28%, and especially the average value of the hyperheuristic algorithm designed under multiconvex passenger flow is up to 28.62%, significantly reducing passengers' waiting time. By comparing the stability of the three passenger flow modes, the results illustrate that the stability of the hyperheuristic algorithm is lower than that of GA. For the smooth passenger flow mode, the stability of medium and lower density of GA is higher than that of the hyperheuristic algorithm. In comparison, the high-density stability of the hyperheuristic algorithm is better than that of GA.

144. Dynamic Multiline Vehicle Dispatching Strategy in Transit Operations

1. Delgado, Felipe
2. IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS
3. 2022

Providing regularity in buses' operation in high-frequency services is essential to offer a good quality of service to users. If buses are not dispatched at regular headways from the terminal, headway irregularity will gradually increase along the line. In this work, we study a vehicle dispatching problem in which multiple lines start their operations from a common terminal where buses can interchange between lines. The model simultaneously decides the ideal dispatching headway for each line and assigns the following arriving buses to the terminal its line to operate and its corresponding dispatching time. The objective is to minimize the dispatching interval's deviation from an ideal headway that is dynamically updated based on the system's status. We formulate our problem as a

> Mixed-integer quadratic problem and adopt a rolling horizon policy to cope with the dynamic and stochastic environment of public transit systems. We prove that a bus assignment that satisfies the FIFO discipline is an optimal solution for the proposed problem. We evaluate our model in a simulation environment under different operational conditions and study the incremental benefits of allowing different flexibility schemes. Our results show that a full flexibility scheme where buses can freely interchange between lines reduces the coefficient of variation of dispatch headways and improves frequency compliance by nearly 20% when compared with the case where buses are restricted to operate in a single line. It also outperforms a myopic heuristic that adopts a a priori target headway. Computational times are compatible with real-time applications.

145. Dynamic Evolution Simulation of Bus Bunching Affected by Traffic Operation State

1. Hu, Shaorong; Zhang, Yuqi; Jin, Yuefei; Dou, Ziqi
2. IEICE TRANSACTIONS ON INFORMATION AND SYSTEMS
3. 2023

> Bus bunching often occurs in public transit system, re-sulting in a series of problems such as poor punctuality, long waiting time and low service quality. In this paper, we explore the influence of the discrete distribution of traffic operation state on the dynamic evolution of bus bunching. Firstly, we use self-organizing map (SOM) to find the threshold of bus bunching and analyze the factors that affect bus bunching based on GPS data of No. 600 bus line in Xi'an. Then, taking the bus headway as the research index, we construct the bus bunching mechanism model. Finally, a simulation platform is built by MATLAB to examine the trend of headway when various influencing factors show different distribution states along the bus line. In terms of influencing factors, inter vehicle speed, queuing time at intersection and loading time at station are shown to have a sig-nificant impact on headway between buses. In terms of the impact of the distribution of crowded road sections on headway, long-distance and con-centrated crowded road sections will lead to large interval or bus bunching. When the traffic states along the bus line are randomly distributed among crowded, normal and free, the headway may fluctuate in a large range, which may result in bus bunching, or fluctuate in a small range and remain relatively stable. The headway change curve is determined by the distri-bution length of each traffic state along the bus line. The research results can help to formulate improvement measures according to traffic operation state for equilibrium bus headway and alleviating bus bunching.

146. Interfering Spatiotemporal Features and Causes of Bus Bunching using Empirical GPS Trajectory Data

1. Shan, Xiaofeng; Wang, Chishe; Zhou, Dongqin
2. JOURNAL OF GRID COMPUTING
3. 2023

> Bus bunching refers to the phenomenon that several buses arrive at a station within a short period. It dramatically increases passengers' waiting time and reduces the quality of transit service. Evaluating the features of bus bunching and identifying the causes are important to developing countermeasures. The primary of this study was to analyze the temporal-spatial features of bus bunching by conducting an in-depth analysis of empirical bus GPS trajectory data obtained in Nanjing, China. The GPS data were inputted into the ArcGIS to track the spatial map's bus trajectories. A data processing procedure was proposed to analyze the data, including data cleaning, trip cutting, each station's arrival and departure time estimation, and time headway calculation. Then the spatiotemporal trajectory picture

was drawn for the bus route where the bus bunching was identified. The study also analyzed the headway features of consecutive buses at the different stations and evaluated the variation of time headway, indicating the severity of bus bunching. The results showed that there are significant differences in the spatiotemporal features of bus bunching between bus stations. When the bus bunching occurred, it persisted on downstream stations for a long time. The bunching severity dramatically increased at downstream stations, reducing bus arrival reliability on the whole bus line. We also identified that the bus bunching was primarily caused by the overlong bus dwelling time at a station and the different travel times of buses between stations. The study fills the gap by developing the methodology to investigate the bus bunching features and causes with point-by-point empirical GPS trajectory data. Findings of the study can also support the real-time prediction and warning of bus bunching in practical applications.

147. Application of modular vehicle technology to mitigate bus bunching

1. Khan, Zaid Saeed; He, Weili; Menendez, Monica
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2023

The stochastic nature of public transport systems leads to headway variability and bus bunching, causing both operator and passenger cost to increase significantly. Traditional strategies to counter bus bunching, including bus-holding, stop-skipping, and bus substitution/insertion, suffer from trade-offs and shortcomings. Autonomous modular vehicle (AMV) technology provides an additional level of flexibility in bus dispatching and operations, which can offer significant benefits in mitigating bus bunching compared to strategies available with conventional buses. This paper introduces a novel alternative to stop-skipping by leveraging the new capabilities offered by AMVs (in particular, en-route coupling and decoupling of modular units). We develop a simple bus-splitting strategy that directs a modular bus to decouple into individual units when it experiences a headway longer than a given threshold. We then use a macroscopic simulation to present a proof-of-concept evaluation of the proposed modular strategy compared to a benchmark traditional stop-skipping strategy and the base (no control) case. We find that the proposed strategy outperforms the benchmark in decreasing each of the three travel time components: waiting time, in-vehicle time, and walking time (which it eliminates completely). It therefore reduces the overhead of bus bunching and thus the travel cost by more than twice as much as the benchmark for busy bus lines. Simultaneously, it also reduces headway variability to a comparable degree. Furthermore, we analyze different control thresholds for applying the proposed strategy, and show that it is most effective when applied proactively, i.e. with the control action being triggered even by small headway deviations.

148. Bus bunching simulation based on the lattice Boltzmann model of traffic flow

1. Wang, Xiaoshi; Liu, Tao; Xu, Meng
2. SIMULATION-TRANSACTIONS OF THE SOCIETY FOR MODELING AND SIMULATION INTERNATIONAL
3. 2023

Bus bunching is a typical phenomenon observed in daily public transit operations and that significantly reduces the reliability and attractiveness of transit service. Although various control strategies, such as vehicle holding, speed guidance, and signal priority, have been proposed to eliminate or alleviate bus bunching, the impact of road traffic flow on bus bunching has not been well studied. To bridge this gap, this work proposes a new mesoscopic simulation model by incorporating the lattice Boltzmann

> model to simulate bus bunching considering the impacts of road traffic flow. Simulation results show that by utilizing the new simulation model, different phase diagrams can be observed. Under different conditions of traffic flow-density evolution, i.e., no oscillation, single oscillation, global oscillation, and irregular oscillation, the resulting bus trajectories are significantly different. In addition, an investigation of a real-world bus line in Beijing with global positioning system (GPS)-based vehicle location data shows that some results of the model are qualitatively consistent with the actual characteristics of the bus route. It shows that the proposed new simulation model has great potential for enhancing our understanding of the impacts of road traffic flow on bus bunching.

149. Holding times to maintain quasi-regular headways and reduce real-time bus bunching

1. Olvera-Toscano, Citlali M.; Rios-Solis, Yasmin A.; Rios-Mercado, Roger Z.; Nigenda, Romeo Sanchez
2. PUBLIC TRANSPORT
3. 2023

> Real-time control strategies deal with the day's dynamics in bus rapid transit systems. This work focuses on minimizing the number of buses of the same line cruising head-to-tail or arriving at a stop simultaneously by implementing bus holding times at the stops as a control strategy. We propose a new mathematical model to determine the bus holding times. It has quadratic constraints but a linear objective function that minimizes the bus bunching penalties. We also propose a beam-search heuristic to reduce computational solution time to solve large instances. Experimental results on a bus rapid transit system simulation in Monterrey, Mexico, show a bus bunching reduction of 45% compared to the case without optimization. Moreover, passenger waiting times are reduced by 30% in some scenarios. For real-world instances with 60 buses, the beam-search approach provides solutions with an optimality gap of less than 5% in less than 3 s.

150. Deep Reinforcement Learning-Based Holding Control for Bus Bunching under Stochastic Travel Time and Demand

1. Liu, Dong; Xiao, Feng; Luo, Jian; Yang, Fan
2. SUSTAINABILITY
3. 2023

> Due to the inherent uncertainties of the bus system, bus bunching remains a challenging problem that degrades bus service reliability and causes passenger dissatisfaction. This paper introduces a novel deep reinforcement learning framework specifically designed to address the bus bunching problem by implementing dynamic holding control in a multi-agent system. We formulate the bus holding problem as a decentralized, partially observable Markov decision process and develop an event-driven simulator to emulate real-world bus operations. An approach based on deep Q-learning with parameter sharing is proposed to train the agents. We conducted extensive experiments to evaluate the proposed framework against multiple baseline strategies. The proposed approach has proven to be adaptable to the uncertainties in bus operations. The results highlight the significant advantages of the deep reinforcement learning framework across various performance metrics, including reduced passenger waiting time, more balanced bus load distribution, decreased occupancy variability, and shorter travel time. The findings demonstrate the potential of the proposed method for practical application in real-world bus systems, offering promising solutions to mitigate bus bunching and enhance overall service quality.

151. Mitigating bus bunching with real-time crowding information

1. Drabicki, Arkadiusz; Kucharski, Rafal; Cats, Oded
2. TRANSPORTATION
3. 2023

> A common problem in public transport systems is bus bunching, characterized by a negative feedback loop between service headways, number of boarding passengers and dwell times. In this study, we examine whether providing real-time crowding information (RTCI) at the stop regarding the two next vehicle departures can stimulate passengers to wait for a less-crowded departure, and thus alleviate the bunching effect. To this end, we leverage on results from own stated-preference survey and develop a boarding choice model. The model accounts for the presence of RTCI and is implemented within dynamic public transport simulation framework. Application to the case-study model of a major bus corridor in Warsaw (Poland) reveals that RTCI can induce a significant probability (30-70%) of intentionally skipping an overcrowded bus and waiting for a later departure instead. This behaviour, in turn, results in significantly lower vehicle headway and load variations, without deteriorations in total waiting utility. Overall, journey experience improves by 6%, and crucially-the prevalence of denial-of-boarding and excessive on-board overcrowding is substantially reduced, by ca. 40%. Results of our study indicate that the willingness to wait induced by RTCI can be a potential demand management strategy in counteracting bunching, with benefits already attainable at limited RTCI response rates.

152. Multi-objective multi-agent deep reinforcement learning to reduce bus bunching for multiline services with a shared corridor

1. Wang, Jiawei; Sun, Lijun
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2023

> Bus bunching is a long-standing problem in transit operation and ruining the regularity of transit service. In a typical urban transit network setting of multiple lines with a shared corridor, bus bunching becomes more frequent as there is more uncertainty inside the shared corridor. While multi-agent reinforcement learning (MARL) has been a promising scheme for learning efficient control policy in a multi-agent system, few studies have explored its applicability in multi-line transit control scenarios. In this study, we focus on a basic transit network where there are two bus lines with a shared corridor. An efficient MARL framework is proposed to learn multi-line bus holding control to avoid bus bunching. Specifically, we design observation and reward functions that incorporate multi-line information. In addition, a preference weights producer is introduced to update the objective weights towards a good trajectory evaluation during daily transit operation. In this way, we handle the multi-objective issue in multi-line control. In experimental studies, we validate the superiority of the method in real-world bus lines. Results show that the state and reward augmented with multi-line information benefit MARL in multi-line bus control. Besides, by updating preference weights towards less passenger waiting time, the regularity of transit service is further improved.

153. Bus splitting and bus holding: A new strategy using autonomous modular buses for preventing bus bunching

1. Khan, Zaid Saeed; Menendez, Monica
2. TRANSPORTATION RESEARCH PART A-POLICY AND PRACTICE

3. 2023

> Autonomous Modular Buses (AMBs) with in-motion transfer capability can be more effective in preventing bus bunching than strategies available with conventional buses, such as bus-holding and/or stop-skipping. We previously proposed bus-splitting, a novel alternative to stop-skipping that directs a modular bus to decouple into individual units when it experiences a longer than normal headway. Despite outperforming stop-skipping, bus-splitting alone cannot eliminate bunching completely since it cannot increase short headways. Therefore, we now propose an integrated strategy that combines bus-splitting with bus-holding so that headways that are both shorter or longer than required can be corrected. We conduct a macroscopic simulation based on a bus route in Hangzhou, China, to compare our combined strategy with standalone bus-splitting as well as stop-skipping combined with bus-holding. Our strategy outperforms the others in terms of reducing both the average travel cost and its variation, limiting the overhead of bus bunching to below 10% under realistic system utilization levels. A bus service adopting the proposed strategy would therefore be more cost-effective, reliable, and attractive for commuters, potentially increasing its ridership and reducing the mode share of private vehicles.

154. Impact Analysis of Traffic Factors on Urban Bus Bunching

1. Pan, Longpai; Zhou, Yu; Meng, Qiang; Wang, Yun
2. IEEE INTELLIGENT TRANSPORTATION SYSTEMS MAGAZINE
3. 2023

> Due to the mixed right-of-way and varying traffic conditions, urban bus operations are often subject to random delays and eventually bus bunching, undermining the schedule reliability. The existing studies have proposed different models to emulate bus bunching and control strategies to mitigate bus bunching, yet few of them considered the effect of the three important traffic factors: intersections with signal coordination, varying traffic volume, and passenger demand. To fill in the research gap, we first define the stop-level frequency of bus bunching events for a bus route in this study. We proceed to present a simulation-based approach to quantify the impact of the three traffic factors on bus bunching. Numerical experiments based on different scenarios are carried out to reveal the cause-effect relationship between these factors and bus bunching events. Contributors to bus bunching are evaluated, and the effect of control delays is examined through statistical measurements. Finally, a real-world case study based on bus route 51 in Singapore is performed, and some insights are provided to alleviate the bus bunching phenomenon.

155. Bus Bunching and Bus Bridging: What Can We Learn from Generative AI Tools like ChatGPT?

1. Voss, Stefan
2. SUSTAINABILITY
3. 2023

> Regarding tools and systems from artificial intelligence (AI), chat-based ones from the area of generative AI have become a major focus regarding media coverage. ChatGPT and occasionally other systems (such as those from Microsoft and Google) are discussed with hundreds if not thousands of academic papers as well as newspaper articles. While various areas have considerably gone into this discussion, transportation and logistics has not yet come that far. In this paper, we explore the use of

> generative AI tools within this domain. More specifically, we focus on a topic related to sustainable passenger transportation, that is, the handling of disturbances in public transport when it comes to bus bunching and bus bridging. The first of these concepts is related to analyzing situations where we observe two or more buses of the same line following close to each other without being planned deliberately and the second is related to the case where buses are used to replace broken connections in other systems, such as subways. Generative AI tools seem to be able to provide meaningful entries and a lot of food for thought while the academic use may still be classified as limited.

156. Real-time cruising speed design approach for multiline bus systems

1. Bian, Bomin; Zhu, Ning; Meng, Qiang
2. TRANSPORTATION RESEARCH PART B-METHODOLOGICAL
3. 2023

> In this paper, we focus on controlling multiline buses operated in networks with curbside bus stops. In such networks, both bus bunching and bus queueing, which often result in passenger inconvenience as well as bus waiting delays, are frequently observed during bus operations. To address the adverse influences of these two phenomena, we propose a mixed integer programming (MIP) model to provide guidance on real-time bus cruising speeds based on the real-time state of the whole system. The proposed model can avoid bus bunching by coordinating bus cruising speeds and alleviate bus queueing congestion by restricting the number of bus arrivals at each stop. Specifically, to address bus bunching, the model has a quadratic objective function that minimizes the total expected passenger waiting time; while for bus queueing, the model has big-M and time-indexed constraints that restrict the number of bus arrivals in each time interval of length g based on the waiting capacity Qs of each stop s. Simulation experiments are conducted with different sizes of virtual networks, and the corresponding results show that the proposed model can lead to both a shorter average passenger waiting time and less bus congestion at stops. The improvement with respect to bus waiting delay is more significant: the percentage decrease can reach 46.9%. Moreover, the results of the average computing time show that the control model can be solved before a bus finishes service in most cases, which means decisions can be fed back to drivers in a timely manner; therefore, the proposed model can meet the requirements of real-time control. A sensitivity analysis with respect to parameters Qs and g is also performed. These two parameters are shown to only affect control performance with respect to bus waiting delays at stops, and shorter bus waiting delays can be achieved with relatively small Qs and large g. Further experiments are conducted within a real network, and the experimental results show that our method is suitable for implementation in practice.

157. Robust Dynamic Bus Control: A Distributional Multi-Agent Reinforcement Learning Approach

1. Wang, Jiawei; Sun, Lijun
2. IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS
3. 2023

> The bus system is a critical component of sustainable urban transportation. However, the operation of a bus fleet is unstable in nature, and bus bunching has become a common phenomenon that undermines the efficiency and reliability of bus systems. Recently research has demonstrated the promising application of multi-agent reinforcement learning (MARL) to achieve efficient vehicle holding control to avoid bus bunching. However, existing studies essentially overlook the robustness

> issue resulting from perturbations and anomalies in a transit system, which is of utmost importance when transferring the models for real-world deployment/application. In this study, we integrate implicit quantile network and meta-learning to develop a distributional MARL framework-IQNC-M-to learn continuous control. The proposed IQNC-M framework achieves efficient and reliable control decisions through better handling various uncertainties in real-time transit operations. Specifically, we introduce an interpretable meta-learning module to incorporate global information into the distributional MARL framework, which is an effective solution to circumvent the credit assignment issue in the transit system. In addition, we design a specific learning procedure to train each agent within the framework to pursue a robust control policy. We develop simulation environments based on real-world bus services and passenger demand data and evaluate the proposed framework against both traditional holding control models and state-of-the-art MARL models. Our results show that the proposed IQNC-M framework can effectively handle the general perturbations and various extreme events, such as traffic state perturbations and demand surges, thus improving both efficiency and reliability of the transit system.

158. Impacts of bus holding strategies on the performance of mixed traffic system

1. Qiang, Shengjie; Huang, Qingxia
2. PHYSICA A-STATISTICAL MECHANICS AND ITS APPLICATIONS
3. 2023

> The holding strategy performs well in resisting bus bunching in the dedicated bus route. Yet, its efficiency in a non-dedicated bus route has not been well studied, and its external effects on other road participants are unclear. We study this topic in a circular two-lane traffic system consisting of buses and cars. A cellular automaton model is used to depict the vehicles' dynamic behaviors. By numerical simulations, we obtained the phase diagram of the bus system, and identified the four states concerning the stability and level of service. Then we analyzed the flow and velocity characteristics and distinguished three states of the traffic system. Our simulations prove the separation effect of car flows on the bus headway regulation. Combined with this effect, the holding strategy makes the bus running more homogeneous and the bus utilization more evenly in the mixed traffic flow condition. Interestingly, from a macro perspective, the holding strategy incurs no detrimental effects on the whole traffic system, though it might intensify local interference between buses and cars near bus stops. Under certain conditions, the average speed of buses and cars increases, eventually increasing the system's capacity.

159. An Online Optimal Bus Signal Priority Strategy to Equalise Headway in Real-Time

1. Zhai, Xuehao; Guo, Fangce; Krishnan, Rajesh
2. INFORMATION
3. 2023

> Bus bunching is a severe problem that affects the service levels of public transport systems. Most of the previous studies in the field of Bus Signal Priority (BSP) and Transit Signal Priority (TSP) focus on reducing a bus delay at signalised intersections and ignore the importance of balancing the bus headways. However, since general BSP methods allocate uneven priorities for individual buses, the headways of bus sequences are prioritised or delayed randomly, increasing the likelihood of bus bunching. To address this problem and to improve the reliability of bus services, we propose an online optimisation model to determine the signal duration and splits for each traffic intersection and each

> signal cycle for bus priority. The proposed model is able to induce the signal timing back to a baseline when the BSP request frequency is low. Using the proposed model, a statistically significant reduction of 10.0% was achieved for bus headway deviation and 6.4% for passenger waiting times. The simulation-based evaluation results also indicate that the proposed model does not affect the efficiency of bus services and other vehicles significantly.

160. Understanding urban bus travel time: Statistical analysis and a deep learning prediction

1. Liu, Yanjun; Zhang, Hui; Jia, Jianmin; Shi, Baiying; Wang, Wei
2. INTERNATIONAL JOURNAL OF MODERN PHYSICS B
3. 2023

> Travel time reliability plays a key role in bus scheduling and service quality. Owing to various stochastic factors, buses often suffer from traffic congestion, delay and bunching, which leads to disturbances of travel time. Automatic vehicle location (AVL) could record the spatiotemporal information of buses, making it possible to understand the status of bus service. In this paper, we specifically analyze the statistical characteristics of travel time based on historic AVL data. Moreover, a Kalman filter-LSTM deep learning is proposed to estimate bus travel time. Numerical tests indicate that the travel time of bus routes shows a left-skewed and right-tail pattern with a good fit of the lognormal distribution. The bus service reliability fluctuates largely in the peak hours, especially the morning peak. Bus bunching and large bus time headway easily occur, and once it occurs, it will continue until destination. The Kalman filter-LSTM model outperforms the ensemble learning methods to predict travel time. This study could provide implications for transit schedule optimization to improve the bus service quality.

161. Decentralized signal control for multi-modal traffic network: A deep reinforcement learning approach

1. Yu, Jiajie; Laharotte, Pierre-Antoine; Han, Yu; Leclercq, Ludovic
2. TRANSPORTATION RESEARCH PART C-EMERGING TECHNOLOGIES
3. 2023

> Managing traffic flow at intersections in a large-scale network remains challenging. Multi-modal signalized intersections integrate various objectives, including minimizing the queue length and maintaining constant bus headway. Inefficient traffic signals and bus headway control strategies may cause severe traffic jams, high delays for bus passengers, and bus bunching that harms bus line operations. To simultaneously improve the level of service for car traffic and the bus system in a multi-modal network, this paper integrates bus priority and holding with traffic signal control via decentralized controllers based on Reinforcement Learning (RL). The controller agents act and learn from a synthetic traffic environment built with the microscopic traffic simulator SUMO. Action information is shared among agents to achieve cooperation, forming a Multi-Agent Reinforcement Learning (MARL) framework. The agents simultaneously aim to minimize vehicles' total stopping time and homogenize the forward and backward space headways for buses approaching intersections at each decision step. The Deep Q-Network (DQN) algorithm is applied to manage the continuity of the state space. The tradeoff between the bus transit and car traffic objectives is discussed using various numerical experiments. The introduced method is tested in scenarios with distinct bus lane layouts and bus line deployments. The proposed controller outperforms model-based adaptive control methods and the centralized RL method regarding global traffic efficiency and bus transit stability. Furthermore,

> the remarkable scalability and transferability of trained models are demonstrated by applying them to several different test networks without retraining.

162. Modelling bus bunching along a common line corridor considering passenger arrival time and transfer choice under stochastic travel time

1. Wang, Zhichao; Jiang, Rui; Jiang, Yu; Gao, Ziyou; Liu, Ronghui
2. TRANSPORTATION RESEARCH PART E-LOGISTICS AND TRANSPORTATION REVIEW
3. 2024

> This study examines bus bunching along a common-line corridor, considering crucial factors underexplored in existing literature, such as stochastic travel times, passenger arrival patterns, and passenger transfer behaviours. We first develop a bus motion model that captures the interaction between bus trajectories and passenger movement. Then we formulate a reliability -based passenger arrival time choice and a transfer choice model to characterise passengers' behaviours. Afterwards, the bus motion model and the passenger choice models are integrated, and a Method of Successive Averages type iterative algorithm is developed to obtain stable passenger arrival patterns and transfer choices. Numerical experiments are carried out on a hypothetical network followed by a case with real-world data. Our findings demonstrate that a high transfer demand could amplify the propagation of bus bunching across lines along the common-line corridor. Meanwhile, a 50% increase in transfer demand leads to a 24%- 30% rise in headway fluctuation. Furthermore, our results suggest that non-uniform passenger accumulation patterns can restore headway regularity as a result of coordinated passenger movement and bus motions, thus alleviating the persistent deterioration in bus bunching.

163. Robust nonlinear decision mapping approach for online bus speed control under uncertainty

1. Zheng, Liang; Liu, Pengjie
2. COMPUTER-AIDED CIVIL AND INFRASTRUCTURE ENGINEERING
3. 2024

> The degradation of bus system attractiveness is primarily caused by low-level service quality and reliability. As an essential technology for bus operation management, online bus speed control has proven to be a flexible and effective solution to mitigate bus bunching and enhance the service level of bus operation systems. In this study, we propose a robust nonlinear decision mapping (RNDM) approach that uses real-time key bus system states to control bus speeds and accounts for uncertainties associated with passenger demands at stations and traffic speeds of interstation links. We develop this approach through a design process that involves learning the input-output mapping relation of a nonlinear programming simulation-based optimization (NLPSO) method using regression tree with AdaBoost. Critical parameters of the fitted regression tree with AdaBoost are then optimized offline using a distributionally robust simulation-based optimization (DRSO) model that is solved by a simulation-based optimization (SO) algorithm. The resulting RNDM method effectively handles two types of uncertainties, expressed by two ambiguity sets of probability distributions, and ensures good bus operation performance even under worst-case uncertainty levels. Numerical experiments reveal that the RNDM, NLPSO, and integer programming SO (IPSO) methods successfully mitigate bus bunching and improve service efficiency and robustness, compared to the no-control scenario. Furthermore, the RNDM method outperforms NLPSO and IPSO in terms of comprehensive performance under uncertainties and demonstrates practical operability. In conclusion, this study

> presents an innovative general framework that uses a nonlinear decision mapping optimized offline by an SO approach to address online simulation-based optimal decision-making problems under uncertainties, which can be applied to solve similar problems.