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【来源：｜发布日期：2021-01-26 】

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入学时间：2009级

答辩时间：2014年

论文题目：基于车路协同的城市道路交通主动控制方法研究

中文摘要

摘要

由于数据采集技术的不断进步，交通控制技术经历了从单点到网络、从离线到在线、从定时到感应，再到自适应的发展阶段，自适应控制系统虽然从原理到架构上都具有明显优势，但在城市中的使用效果并不理想，究其原因，首先是因为基于线圈等检测设备的交通流数据采集方式属于断面检测方式（Point Detection），无法及时有效并准确地获取交通控制所必需的基础输入信息，如交通流何时到达对应的交通流到达时刻信息、交通流往哪去对应的交通流路径（左转、直行、右转）信息，由于无法准确及时地获取此类信息导致控制模型的真实效益无法充分发挥。其次，由于受现有交通控制策略的约束，现有交通控制系统的数据来源主要为线圈检测器，控制手段为信号灯控制，控制方法的工作机制在本质上属于基于数据驱动的被动控制，即通过“检测器→信号控制系统”的单向信息传递，根据检测数据调整信号配时用以适应交通流的到达，然而，信号配时的改变势必导致下游交叉口交通流到达的改变，从而进入交通流的波动导致控制方案的变化，控制方案的变化又导致交通流更大波动的恶性循环。

2005年以来，车路协同技术稳步发展并逐渐成熟，“车路协同技术”旨在通过智能车载单元与智能路侧单元的双向、实时与高效地信息交互，在为驾驶人提供辅助驾驶信息的同时，进一步实现车路间的最佳协调，提高交通效率与安全。首先，车路协同技术的引入，将进一步推动数据采集技术的进步，相对于基于线圈等检测器的定点数据采集方式，在车路协同环境下能实时地获取车辆的速度、位置、轨迹、甚至出行路径等信息，使交通控制系统有条件在更加完善的数据与信息环境下计算出更优的控制方案，从而进一步降低延误，提高交通流运行效率。其次，借助车路协同技术，车辆与交通控制系统将突破单向信息传递，基于车路协同技术的双向通信实现双向信息交互，将导致用于交通控制的输入数据可直接来源于车辆，控制手段也将不局限于信号灯，而能够通过速度引导等方式直接作用于车辆，从而使交通控制实现从对交通流的被动适应到主动引导的转变，在此基础上，本文提出主动交通控制的概念，设计控制机制并研究相应的控制方法。

首先，本文设计了基于车路协同技术的主动交通控制系统的工作机制。重点探讨如何将车路协同技术应用于现有交通控制系统，探索车路协同技术与交通控制系统的相互作用原理，分析系统的组成要素、逻辑结构、物理结构、数据与信息的流向及共享方式，在此基础上提出系统的工作原理与优化流程。

其次，本文在单交叉口层面，研究了车路协同环境下基于引导的主动交通控制方法。现有交通控制系统大多将交通流到达数据作为优化信号配时方案的输入，而本文基于车路协同技术的双向通信，能够引导交通流到达，基于此研究思路，本文在分析了红灯引导模型、绿灯引导模型和车队划分模型的基础上，结合信号控制模型、延误预测模型、停车次数预测

模型提出了同时优化交通流到达与交通控制方案的集成优化模型，模型输出信号配时方案与交通流到达即行驶车速数据，并利用滚动时间窗的方法进行优化。

再次，本文在多交叉口层面，研究了车路协同环境下基于路径的协调控制方法。由于现有的数据采集手段无法直接获取协调控制的两个关键参数：分别是交通流路段行驶车速与路径流量（到达下游交叉口时左转、直行或右转），而只能采用经验、估计和预测的方法进行估测。然而，基于车路协同技术能够对路段车速进行主动引导，更能提前获知路径流量参数，从而能准确度量交通流何时到达，往何处去，提高协调控制的准确度和效益。在此基础上，本文首先提出了以交叉口间的通行能力匹配为目标的同时优化左转相位与信号配时的组合优化模型；其次，提出了以双向协调路径的路径流量和行驶车速的乘积最大为目标的同时优化双向协调路径、相位差和路段行驶车速的集成优化模型。

最后，本文研究了基于车路协同的时空优先控制方法。优先控制是将车路协同技术应用于实地交通控制的第一步，也是现阶段在实地交通控制中能较快实现的功能。因此，本文基于车路协同技术，重点以公共汽车交通优先控制为例，分别从空间优先和时间优先的角度提出了公共汽车交通优先控制方法，在保证交通流总体效益最大化的同时，实现公共汽车交通的优先通行。

本文从数据采集技术的进步与交通控制系统发展历程的角度出发，分析并提出“城市道路交通主动控制”的概念，对基于车路协同的交通控制方法进行了探索性研究，拓展了交通控制的内涵与外延，对后续相关研究也有一定的借鉴意义。

关键词：交通控制，主动控制，车路协同，控制机制，车速引导，路径流量，优先控制

英文摘要

ABSTRACT

Due to the continuous improvement of data collection techniques, Traffic control technology had passed through various stages of development including from single-point control to network control, from off-line control to on-line control, from fixed-time control to actuated control, from actuated control to adaptive control. Although adaptive control systems have obvious advantages on operating principle and system architecture, the practice proves that the effect of adaptive control systems is not good. There are mainly two reasons that restricting the performance of adaptive control systems. Firstly, most of the adaptive control systems are based on loop detection that is only able to collect traffic data from a single point, and is not able to efficiently and correctly collect some of the key parameters for traffic control such as arrival time and travel path of traffic flows. This may cause adaptive control systems are not able to reach their full potential in urban traffic control. Secondly, because of the restrictions of the existing traffic control strategy, the inputs for adaptive control systems mainly come from loop detectors, the control measure is based on traffic signal lights, the operating mechanism of adaptive control systems can be considered as passive control that based on data-driven processing. That is, by means of one-way data transmission, which is from detectors to traffic control systems, adaptive control systems would modify the signal timing to adapt the arrival of traffic flows. However, the arrival of traffic flows at the downstream intersection can certainly be changed duo to the modification of signal timing at the upstream intersection. Thus a vicious circle will be set up. That is, the fluctuations of traffic flows could cause the modification of signal timing. The modification of signal timing will then cause more extreme fluctuations of traffic flows.

Since 2005, the technology of “VII” (Vehicle Infrastructure Integration) has made steady progress and become increasing maturity. VII is aiming to improve traffic efficiency and safety by means of the high-efficiency, real-time and two-way communication between OBU (On Board Unit) and RSU (Road Side Unit).

Firstly, with the introduction of VII to traffic control systems, compared with the existing point detection method, the speed, position, trajectory, even travel route of every single vehicle can be collected in real-time within VII environment. This makes traffic control systems can work out better signal timing programs based on better data inputs. Thus further decreases traffic delays and improves traffic efficiency. Secondly, by means of VII, the two-way communications between vehicle and traffic control systems can be set up, which result in the inputs for traffic control will directly come from vehicle. And the control method will not just be restricted to take use of traffic signal lights; moreover, speed guidance can be employed to guide the arrival of traffic flows. This makes the traffic control strategy changed from passive adaption to active guidance. Then the concept of active traffic control has been proposed based on these academic ideas. This thesis will focus on the active control mechanism and active control methods.

Firstly, the working mechanism of the active traffic control system has been proposed. In this section, how to integrate VII and the existing traffic control system is mainly discussed. To begin with the studies of the interaction between VII and traffic control system, then the components, logical structure, physical structure, data and information flow of the active traffic control system are analyzed. Finally, the operating principles and the optimization flow are proposed.

Secondly, the active traffic control methods based on speed guidance within VII environment at a single intersection have been researched. Most of the existing traffic control systems treat the arrival time of traffic flows as an input before optimizing the signal timings. However, in this thesis, based on the two-way communication of VII, the arrival time of traffic flows can be determined by speed guidance. Based on this idea, the “speed guidancemodel during red”, “speed guidancemodel during green” and the “platoon dividing model” have been discussed. Then the integrated model that can simultaneously optimize the arrival of traffic flows and traffic signal timings are proposed based on “traffic control model”, “delay forecasting model” and “number of stops forecasting model”. The outputs of the integrated model including the traffic signal timing programs and the travel speed of traffic flows. The sliding time window technique is adopt to optimize the parameters.

Thirdly, a route based integrated signal coordination control method has been proposed within VII environment at multi-intersections. The two key parameters for signal coordination control that include travel speed and route volume can not be collected based on existing data collection techniques. However, with VII technology, the travel speed can be guided; the route volume can be directly collected. Thus the signal control systems can accurately measure when traffic flows arrive and where traffic flows go to (turn left, go straight or turn right). Based on this idea, firstly, with the objective of minimizing capacity gap, an integrated optimization method for simultaneously optimizing left turn phases and signal timings is proposed. Secondly, with the objective of minimizing output volume multiply by travel speed, an integrated signal coordination control model has been proposed to optimize the coordinative routes of both directions, dynamic travel speed, and specific signal offsets.

Finally, the temporal and spatial bus priority traffic control methods within VII environment have been present. Priority traffic signal control is the first step to apply VII technology to field traffic control. Therefore, this thesis focuses on the temporal and spatial priority traffic control methods based on VII technology. The objective of the methods is aiming to maximize the overall benefits of traffic flows in the same time give priority to buses.

Thisthesisbegins with the improvement of data collection techniques and the development of the traffic signal control systems. Then the concept of active traffic control has been proposed and analyzed.This thesis makes an exploratory research on traffic control methodsbased on VII technology. And the study enriches theconnotation and extensionof traffic control systems, also will bring some references to follow-up studies.

Key Words:traffic control, active control, Vehicle Infrastructure Integration, control mechanism, speed guidance, route volume, priority control.

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入学时间：2009级

答辩时间：2014年

论文题目：基于起点的交通网络均衡分配算法研究

中文摘要

摘要

基本的用户均衡（User Equilibrium, UE）分配模型是估计和预测出行者在道路网络上路径选择的主要方法之一。由于模型输入简单，输出结果唯一稳定，能够有效应对大规模的交通网络等特点，该模型在过去几十年中被大量研究和广泛应用。本文将对一类能够高效求解基本交通分配模型的新型算法进行研究—本文称该类新算法为基于起点的（origin-based, OB）交通分配算法。基于起点与传统的基于路段（link-based）和基于路径（route-based）的概念相对应，主要是指算法以基于起点的流量（origin-based flow）为变量计算交通分配问题的下降方向。基于起点的算法将交通网络分解为与起点（origin,O）数量相同个子网络，每个子网络由一个起点和从该起点到所有终点（destination, D）的路径（至少存在一条路径以保证子网络的连通性）构成。基于起点的交通分配算法的基本思想可以总结为：通过为每个起点存储和维护一个子网络，可以将从一个起点到所有终点的交通需求限制仅分配到与该起点对应的子网络上；在每个子网络上建立并求解均衡分配问题首先实现子网络的用户均衡分配，然后再通过在所有的子网络间循环迭代实现整个网络的用户均衡分配。

目前，对于基于起点的交通分配算法的研究正处于探索阶段。已有研究聚焦于新算法的提出，缺乏对该类算法系统的研究、对比和评价，对决定算法收敛精度和效率的原理和方法认识不够清晰。本文将对现有算法进行深入研究的基础上，完善基于起点的交通分配算法体系，着重从算法思想、原理方法和收敛特性三个方面对该类算法进行深入的分析和对比研究。研究成果一方面揭示了不同算法之间的相互联系与差异，给出了影响算法效率和精度的关键因素；另一方面本文利用得到的研究成果对现有的算法进行了改进，为设计高效的交通分配算法提供参考。此外，本文还将基于起点的算法扩展到了用于求解多用户和多用户多准则交通分配问题。

首先，对基于起点的算法思想、表达式和用户均衡条件进行了研究，建立了一个通用的基于起点的算法基本框架，并在此框架基础上证明了基于起点的算法的收敛原理（第二章）。

其次，对基于起点的交通分配算法采用的基本原理、求解方法和收敛特性进行了系统的分析和研究，着重研究了不同算法之间的差异，并分析了这些差异给算法带来的可能影响（第三章和第四章）。OBA（origin-based algorithm）、LUCE（local user cost equilibrium）、QBA（Nie’s revised OBA）和B（Dial’s B algorithm）算法又被称为基于丛的算法（Bush-based Algorithm, BA），因为它们维护的子网络都是不包含有向环的丛结构（bush）。本文证明了LUCE

算法与OBA算法在表达式、点子问题的分解方法以及近似方法等多个方面是完全一致的，它们之间的关键区别在于采用了不同的方法求解近似的二次规划问题：LUCE采用的是所谓的贪婪（Greedy）算法，而OBA采用的是梯度投影（Gradient Projection, GP）算法。尽管Greedy算法被证明在求解二次规划问题时具有更高的求解效率，然而本文的数值实验发现LUCE算法在收敛较高精度后（10^{-10}左右）后，收敛速度会突然大幅度变慢，甚至会停止继续收敛。第四章的分析结果表明造成该收敛特性的主要原因是由于LUCE算法无法准确的计算二阶导数，由于二次规划问题本身是对原问题的近似，利用Greedy算法准确的求解二次规划问题反而打断了LUCE算法的连续收敛。QBA算法是OBA算法的一个变体，它通过采用更频繁的路段更新策略而使它在求解中小规模或者拥挤程度不高的网络时具有了更高的收敛效率和精度。

本文对B、TAPAS（traffic assignment by paired alternative segments）和ANST（adapation of network simplex for the traffic assignment problem）三种算法的算法原理和收敛特性的研究成果表明基于路径流量的子网络均衡策略能够明显提高OB算法的收敛效率和精度，这是因为该策略一方面避免了对点子问题的分解而大大降低了算法的复杂度；另一方面因为无需对原问题进行近似而可以准确的计算两条路径之间的转移量。B算法在从上通过将流量从最长路径直接向最短路径转移而避免了存储路径，使它的收敛效率和精度明显高于其它的BA算法。TAPAS算法突破了从结构限制，通过借鉴B算法中从最长路径向最短路径转移流量的算法思路，创造性的利用PAS（Pair of Alternative Segments）结构实现子网络的流量均衡调整。通过存储一系列PAS，TAPAS算法能够同时为多个子网络的多条路径转移流量。ANST算法可以认为是部分的扩展了TAPAS算法中PAS结构，将PAS的结构扩展为更一般的无向环；ANST更借助生成树可以快速的搜索无向环，提高了在网络上搜索无向环的效率。然而，遗憾的是ANST算法似乎无法像TAPAS算法一样将搜索到的无向环保存起来，以便重复利用。除此之外，B算法在收敛过程中需要建立最优的丛结构，ANST算法需要建立最优的树结构，这在一定程度上阻碍了它们在高精度阶段的收敛效率。本文的数值计算结果进一步验证了以上分析，TAPAS算法的收敛效率和精度在所有的算例中均领先其它所有的OB算法。

最后，本文将基于起点的交通分配算法应用于求解多用户分配（multi-class assignment）和多用户多准则分配（multi-class multi-criterion assignment）问题（第五章）。在以车辆类型为分类标准的多用户分配模型中，本文利用VISUM中带等比例条件（Proportionality Condition）的LUCE算法对芝加哥区域模型进行了求解，并获得了一个唯一的用户路段流量解。从路段、PAS和网络三个层面对等比例条件的影响作用进行了分析。在多用户多准则分配问题中，本文设计了一个能够求解有限维模型的OB算法框架。通过提前将连续的时间价值分布函数近似为离散分布函数，以上算法框架也可以用于求解无限维模型。以B算法为基础设计的MCB（multi-class B algorithm）算法能够有效的求解有限维的多用户多准则分配模型。与T2算法的计算结果对比表明，当离散为足够多的分类时，MCB算法能够以更高的精度求解无限维的多用户都准则分配模型。

本文对基于起点的交通分配算法体系进行了清晰的描述，对基于起点的算法思想、理论方法和收敛特性进行了系统而深入的分析和研究。本文的主要研究成果和创新点总结如下：（1）次对基于起点的交通分配算法进行了系统研究，完善了基于起点的算法体系；（2）本研究表明OBA算法与LUCE算法的算法原理非常相似，证明了无法准确计算目标函数的二阶导数和其采用的Greedy算法是导致LUCE算法不能持续收敛的主要原因；同时证明了前者也是阻碍OBA算法的收敛效率进一步提高的关键因素；（3）分别对B算法、TAPAS算法和ANST三个算法的算法原理和收敛特性进行了详细研究，对比分析了它们之间的联系与差异，总结了三个能够提高OB算法效率的影响因素；（4）首次对所有的基于起点的算法(已经发表)进行了编程实现，并利用不同规模的交通网络对它们的收敛精度和收敛效率进行了直接对比。分析了基于起点的算法对网络大小和拥挤程度的敏感性，证明了O-D对的数量是决定交通分配算法计算时间的主要因素；（5）对利用等比例条件和基于起点的算法如何在多用户交通分配问题中确定唯一的用户路段流量进行了研究，从路段、PAS结构和网络三个层面分析了等比例条件对多用户交通分配结果的重要影响，研究成果表明在多用户交通分配问题中不添加等比例条件得到的用户路段流量大多数情况下是无效的；（6）首次将基于起点的交通分配算法用于求解多用户多准则分配问题，提出了能够求解有限维模型的基于起点的算法框架，并利用一个算例证明了该框架同时能够有效的求解无限维模型。

关键词：用户均衡，基于起点的算法，基于丛的算法，多用户多准则分配问题，等比例条件

英文摘要

ABSTRACT

The static user-equilibrium (UE) traffic assignment model is widely used in practice, and finding equilibrium flows on real networks has always been a very challenging subject. A new class of algorithms featured by "origin-based"(OB) has attracted much attention in recent years, especially realizing its capability to obtain sufficiently precise solutions in a reasonable time. The basic idea of origin-based algorithms is to solve the UE flows restricted in a single origin network and loop among origins to produce the all-origin to all destination equilibrium flow. Despite a succession of new origin-based algorithms have been proposed, a comprehensive study of such class of algorithms, including algorithm theory, employed methods, convergence precision and speed, has not been seen in the current literature, and which will be focused on in this doctoral research. Moreover, we also attempt to expand the origin-based algorithms to solve the multi-class and multi-class multi-criterion traffic assignment problems.

The basic idea, formulations and UE conditions of origin-based algorithms are examined in the second chapter. An algorithm framework that is suitable for all origin-based algorithms is designed, and we prove that all algorithms can converge to a UE solution based this framework.

The theory, methods and convergence performance of origin-based algorithms are studied and analyzed extensively in Chapter Three and Four. All origin-based algorithms are classified into two groups by their structure and performance. OBA (Bar-Gera’ s origin-based algorithm), QBA (Nie’ s revised OBA) and LUCE (local user cost equilibrium) are known as bush-based algorithm as well due to their specific sub-network named bush, which is an acyclic subnetwork that intends to encompass all UE shortest paths. We show that algorithm OBA and LUCE are equivalent with each other in many aspects except one key difference that they employ different methods to solve the quadratic approximation of node-based subproblems, Gradient Projection (GP) method by OBA and Greey method by LUCE. While the greedy algorithm accelerates the solution of the subproblems and reduces the cost of line search, it unexpectedly disrupted the overall convergence performance in our experiments, which consistently show that LUCE failed to converge beyond certain threshold of relative gap. Our analysis suggests that the root cause to this interesting behavior is the inaccurate quadratic approximation constructed on faulty information of second-order derivatives. Because the quadratic approximations themselves are inaccurate, the search directions generated from them are sub-optimal. Algorithm QBA is a variant of OBA by updating the cost and derivative of relevant links immediately after each the node-based subproblem is solved, the numerical experiments shows that the performance of QBA is far improved in solving medium and small networks.

Although algorithm B is in the "bush" family as well, the convergence performance of it outperforms the above three ones. Our analysis suggest that the better performance of B mainly comes from the route-flow-based bush equilibration strategies, in which flows are swapped from longest route to shortest route. Inspired by this smart idea, algorithm TAPAS (traffic assignment by paired alternative segments) further develops a similar structure named "Paired of Alternative Segments (PAS)". TAPAS searches and keeps a list of PASs iteration by iteration. By swapping flows between two segments in a PAS, TAPAS can equilibrate flows for multiple routes in multiple subnetworks simultaneously, which fasten TAPAS's performance. Algorithm ANST (adapation of network simplex for the traffic assignment problem) generalizes the concept of PAS into an undirected cycle and employs the structure of Network Simplex Method to help to search cycles. Our numerical

experiments show that the performance of ANST is pretty close to algorithm B, and not better than TAPAS in both convergence precision and speed. A comparison of these three algorithms and a reasonable explanation are given in Chapter Four.

Another contribution of this research is to expand the origin-based algorithms to solve the multi-class and multi-class multi-criterion traffic assignment problems. In the multi-class traffic assignment model where all travellers are classified by vehicle type, an additional condition named "proportionality condition" is added as an post-processing stage for algorithm LUCE in VISUM, and then they are used to solve the Chicago Regional model to obtain a unique class link flows solution. The effects of proportionality are analyzed in the level of link, PAS and the overall network. In the case of multi-class multi-criterion assignment problem, an origin-based algorithm framework is proposed to solve the finite model. For the infinite model, we can transform it to a finite model by discretizing the continuous VOT (Value of Time) distribution into a discrete one, and then solve it by the proposed algorithm framework. Algorithm B is revised into a origin-based finite multi-class multi-criterion algorithm using the above framework in our research, the numerical comparison with the infinite algorithm T2 developed by Dial shows that the proposed algorithm can provide more precise solution when the class number is enough large.

Key Words:user equilibrium problem, origin-based algorithm, bush-base algorithm, multi-class multi-criterion traffic assignment problem, Proportionality Condition.

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入学时间：2009级

答辩时间：2015届

论文题目：公共交通运行服务理论与优化方法

中文摘要

摘要

城市公共交通系统是一个人、车、路、信息与规则（管理措施）动态交互作用的复杂系统，公共交通服务实施效果（包含提供的服务品质与乘客的满意度）是公交乘客与系统其他对象之间动态交互作用的结果。公交运行服务过程，即公交乘客出行过程与公交车辆行驶过程之间的动态交互作用过程，是公交服务产出的关键环节；运行服务过程当中公交乘客出行服务需求与公交系统服务供给之间的匹配程度决定着当前服务资源投入条件下公交系统服务供给被有效利用的程度以及公交乘客出行服务需求被有效满足的程度。本文以公交运行服务过程为研究对象，研究如何去客观测度运行服务过程当中服务供给与需求之间的匹配程度，以及如何优化现有的服务改善措施从而进一步提升公交运行服务效果。文章主要研究内容分为如下几个方面：

首先，本文通过解析公交乘客出行过程及其服务需求特性与公交车辆行驶过程及其服务供给特性，研究如何客观测度公交系统服务供给与公交乘客出行服务需求之间的有效匹配程度；具体而言，以公交站点与站间服务过程为测度对象，针对站点及站间运行服务效率与可靠性的测度问题给出了指标的定义及其计算方法。然后面向运行服务优化问题，在总结分

析现有的服务改善措施基础之上，提炼出面向公交系统外部通行条件、企业运营管理以及乘客出行信息服务三个维度的五个运行服务改善措施优化问题，并在随后论文研究当中给予了解决。

在面向外部通行条件的运行服务优化方法研究当中，以如何优化外部通行条件改善措施的实施位置从而最大程度提升乘客出行时间节省为研究问题，通过分析路段专用道设置以及信号控制交叉口公交优先通行控制对乘客出行时间节省的灵敏度参数，构建面向乘客出行时间最大程度节省的专用道设置路段与优先通行控制信号交叉口最佳实施位置选择方案，为公交系统外部通行条件改善措施实施位置的选择提供了备选优先对象。

在面向企业运营管理的运行服务优化方法研究当中，首先以公交乘客站点候车时间最省为优化目标，通过解析研究得出均衡候车时间发车间隔方案可以较大程度降低乘客总候车时间，同时与均匀间隔发车方案与均衡载客发车间隔方案对比发现，均衡候车时间发车间隔方案能够兼顾均匀发车间隔方案下站点候车时间可靠性高与均衡载客发车间隔方案下车内拥挤程度低的双重优点。随后，面向如何在中途站点维持计划服务间隔的研究问题，本文构建了基于公交车辆运行状态的动态调度控制模型，并重点针对控制模型当中的核心问题——如何识别与划分公交车辆运行状态展开了深入研究，通过理论解析研究发现公交车辆运行车头时距偏差与车辆行驶时间之间存在一定程度的线性关系，以此为基础提出运行车头时距偏差随着车辆行驶时间比例放大的理论模型，并对该模型成立的边界参数给出了标定方法。

在面向出行信息服务的运行服务优化方法研究当中，以如何优化发布出行前出行时间预算信息使得乘客出行时间成本最低与如何优化发布在途站点公交车辆到站时间信息使得乘客候车时间成本最低为研究问题，首先构建了公交乘客出行时间预算与出行时间成本之间的模型，并以乘客出行时间成本最低为优化目标求解最佳出行时间预算，同时研究发现最佳出行时间预算与乘客出行活动需求之间密切相关，因此建议根据出行活动需求的差异特性提供多级出行时间预算信息服务；随后，针对乘客站点候车过程当中有效利用候车时间短期出行的潜在需求，分析了到站时间信息服务条件下乘客的候车行为以及对候车时间的影响，以此为基础构建了公交乘客站点候车时间成本模型，并以乘客候车时间成本最低为优化目标求解最佳公交车辆到站时间发布值，研究结果表明最佳公交车辆到站时间发布值取决于信息服务系统车辆到站时间预测的精度、乘客短期出行时间的不确定程度以及班次服务间隔三方面因素，在合理的变量分布假设条件下本文给出了最佳发布到站时间的数值求解算法。

本文研究成果对于如何在一定服务资源投入条件下最大程度提升公交乘客对公交系统服务的满意程度具有较强的理论指导意义与实践操作价值。

关键词：公共交通，运行服务，优化方法

英文摘要

ABSTRACT

The public transit system is a typical complex system that contains the dynamic interaction among passengers, vehicles, infrastructure, information service, and management rules. The service effectiveness, including the service quality provided and service satisfaction of passengers, is the result of such dynamic interaction. Transit running service process, which is the dynamic interaction between the travel process of passengers and the running process of bus vehicles, is the dominant process for the service output of transit system, because the matching degree between the travel process of passengers and the running process of bus vehicles determines the effective use of service input resources and the satisfaction degree of passengers. This research focused on the transit running process, considering how to objectively measure the service effectiveness of transit running service process, and how to further optimize service improvement methods to improve transit service performance. The main research contents are as follows:

Begin with the analysis of the travel process and service demand of passengers and the running process and service supply of vehicles, service indexes, including the service efficiency and reliability at stops and between stops, were formulated to measure the matching degree between service demand and service supply of transit running service process. Five basic service optimization problems were presented and corresponding solving methods were given in the following content.

On how to optimize the external running environment of bus transit system to improve service efficiency, this research focused on how to choose the optimal position to reduce passengers' travel time at most, by analyzing the sensitivity coefficient of passengers' travel time reduction when bus lane or bus priority control is adopted, which provides priority options for improve the external infrastructure of bus transit system.

On how to better operate and manage bus transit system, firstly, this research analyzed the effect of departure timetable on passengers' waiting time at downstream stops, and analytical model shows that passengers' waiting time will reach a low value under the equilibrium waiting time scheme. By comparing it with equilibrium interval scheme and equilibrium load scheme, the proposed equilibrium waiting time scheme can improve the waiting time reliability and reduce the unbalanced load at the same time. Then, on how to maintain the departure schedule at downstream stops, a control model based on vehicle travel state was established, and different control measures were suggested under different service state. Specially, how to recognize vehicle travel state and calibrate its boundary parameters were perfectly solved in this research because analytical model shows that headway deviations are approximately linear correlated to vehicle travel time.

Finally, on how to optimal broadcast travel information to help adjust passengers' travel behavior, this research mainly studied how to provide the optimal budget travel time to minimize passengers' total travel time cost and how to advertise the optimal bus arrival time to minimize passengers' waiting time cost. For the former research problem, the effect of budget travel time on passengers' travel time cost was modeled, and the optimal budget travel time was analytically solved, which is found to be highly related to passengers' travel demand, so a multi-stage pre-travel budget travel time information service was suggested in this research. Then, the effect of advertised bus arrival time on passengers' waiting time cost was analyzed, and the optimal bus arrival time to be broadcasted is found to be highly related to prediction accuracy of bus arrival time, uncertainty of passengers' short-return travel behavior, and the service interval between the oncoming bus and the next bus. Under reasonable distribution assumptions of such variables, this research gave a numerical example on how to calculate the optimal advertised bus arrival time.

Overall, the research results will be of great value for improving passengers' service satisfaction under limited input of service resources, from both the theoretical and practical point of view.

KEY WORDS: Public Transit, Running Service, Optimization Method

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入学时间：2009级

答辩时间：2015届

论文题目：城市公共交通使用影响因素及其作用机制

中文摘要

摘要

城镇化和机动化水平的提高，极大地提升了我国城市居民的日常活动强度和范围，个体机动化出行强度及其在全方式出行中所占的比例显著增加，给有限的城市道路资源带来巨大压力，引发了包括交通拥堵、车源污染等诸多城市交通问题。鉴于此，我国政府提出了“优先发展城市公共交通”的战略，旨在引导城市居民出行向集约化的公共交通方式转移，以冀达到平衡交通供需、缓解城市交通矛盾的目的。但在实际操作中，战略层面的“公交优先”并未有效地转化成战术层面的交通需求管理措施，公共交通分担率和人均出行乘次在许多城市不升反降。造成这一现状的重要原因之一就是当前对我国公共交通使用影响因素的理论和实证研究尚难以有效支撑城市交通需求管理的政策实践。本研究即以此为背景开展工作，并在以下六个方面取得了一定的突破：

（1）基于全国30个省会城市的1998-2011年的统计年鉴数据，以GDP、城市人口、建成区面积、城市道路铺装面积、公共汽电车保有量、私家车保有量、可支配收入以及城市地理区位作为自变量，建立了城市公共汽电车客运量的城市固定效应面板模型。对模型的分析表明：①与经济发展水平指标相比，人口增长对于城市公交客运量增长的促进更为显著；②公共汽电车客运量对以万人公共汽电车保有量为表征的服务供给规模的弹性为0.43＜1，表明单纯增加公共交通服务供给并不能高效地转化为公共交通客运量的增长；③从弹性的角度来看，私家车对公共汽电车客运量具有显著的抑制作用，且这一影响在东部城市要显著高于中西部地区城市；④不同地理区位的城市公共汽电车客运量存在空间异质性：东部城市凭借较为发达的社会经济活动以及较为充足的人均道路和公共交通资源供给，较中西部城市更容易诱发较高的公交客运总量。研究对于城市公共交通客运量的估算以及交通需求管理政策的差异化有指导意义。

（2）通过对乘客公交出行过程的系统分析，将公共交通服务质量细化为若干评价项目，依据乘客对服务质量的主观感知与期望之差来定义单个评价项目的服务质量，并根据乘客的感知重要程度对单个指标加权后得到整体的服务质量。通过对典型线路的实证分析表明，所提出的方法可以有效测度线路级别的公共交通服务质量，并识别对乘客感知服务质量有关键作用的短板。

（3）以北京新近开行的定制商务班车乘客为研究对象，对比了原公共交通通勤者和原私家车通勤者出行方式变化前后在货币费用、出行舒适度、出行总时耗和有效利用时间的变化，以及乘客为服务改善额外支付货币费用的意愿，研究表明，相较于总出行时间的改善，通勤群体更为关注出行时间中可以有效利用的比例，且愿意为提高这一比例放弃个体机动化交通工具并额外支付一定的货币费用，本部分研究对于提高公共交通相对于个体机动化交通的竞争力有启发意义。

（4）基于公交车载GPS记录的车辆轨迹数据、IC卡交易记录数据以及静态公交网络GIS数据，设计了公交乘客换乘信息的提取方法以及换乘时空分布特征的计算方法。对宁波市公交数据的实证分析表明所提出的方法可以有效识别换乘信息，而设计的换乘服务时空评价指标并较好地反映公交出行换乘集中发生的时空区域、长时间换乘发生的线路/站点位置以及步行距离较长的换乘站点对，可以作为评价和改善公共汽电车运营组织方案的技术依据。

（5）根据家庭成员数量、血缘和婚姻关系以及家庭中的子女情况（包括有无子女和子女学段）构造“家庭生命周期阶段”作为新的家庭特征指标变量，基于宜昌市的居民出行调查数据，分析了①包括“家庭生命周期阶段”在内的家庭社会经济特征、个体机动化交通工具保有状况、家庭成员个人社会经济特征、出行特征以及家庭住址周边的公共交通服务水平等因素对家庭成员出行方式选择行为的影响；②上述因素对家庭机动化交通工具保有状态的影响；③处于不同生命周期阶段的家庭在机动化交通工具保有以及出行方式选择行为上的差异。研究发现，引入新变量后各模型对数据的解释能力增强；处于生命周期不同阶段的家庭出行需求存在显著差异，若家庭周边的公共交通服务无法有效满足家庭成员的出行需求

且经济条件支持，购置机动化交通工具以及家庭成员出行时更多的使用个体机动化交通工具可能性显著升高。与将多个家庭属性单独引入模型相比，采用新变量有效缓解了自变量的多重共线性，提升了模型对数据的解释能力，同时也有更为明确的行为机制。

（6）基于以上海市民为对象的问卷调查数据，应用结构方程建模方法建立了计划行为理论和规范激活理论的整合模型，从社会心理学的角度研究了来自外界的主观社会规范和描述性规范以及来自个体内部的个人规范对实际交通工具保有状态、出行意愿以及出行方式选择行为的影响。对模型的分析表明：①收入水平的上升并不会直接导致个体公共交通出行意愿以及实际公交出行强度的下降，而是要受到私家车保有状态的中介作用：有私家车群体的公共交通出行意愿和实际出行强度显著低于无私家车群体，而高收入群体的保有私家车的概率较高；②鼓励使用公共交通出行的主观社会规范、个人规范、描述性规范（包括家庭和非家庭描述性规范）均会强化个体采用公共交通出行的意愿并增加其实际公交出行频率；③对于过度依赖私家车出行造成的负面影响的认识会显著影响使用公共交通的个人规范，其中，对空气中颗粒物质(PM2.5等)浓度以及道路交通拥挤程度的感知对个体选择公共交通出行意愿的影响强于对社会排斥、个人健康、能源危机以及交通事故感知的影响，奠定了基于心理决策机制的非强制性交通需求管理政策的理论基础。

关键词：城市公共交通，公交客运量，公交服务质量，家庭交通工具保有，社会心理因素

英文摘要

ABSTRACT

In the past decades, China has been experiencing the most rapid urbanization and motorization. As urban citizen travel more and further, the individual mobility share keeps increasing, which brings much urban traffic problems, e.g., traffic congestion, and air pollution. Thus the transit priority development strategy is proposed to shift travelers to greener transport with high qualified public transport service as well as auto purchasing and usage regulation. With good intentions, the implementation results is not encouraging, both the public transport usage per capita and the share don’ t increase as expected, or even decrease in some cities. One important reason is the lack of theoretical and empirical study on the impacts of public transport usage determinants. The current study is targeted to fill the gap to some extent.

(1) Urban public transit ridership determinants are studied with data collected from the annual statistic book from the year of 1998 to 2011. An individual fixed effect panel data model is formulated and calibrated, with GDP, population, built area, road pavement area, bus and tram fleet size, private car ownership, disposable income per capita and geographical location as the explanatory variables. Comparing the coefficients, we found that 1) the increase of population is a more important driver than economic development, regarding public transit ridership; 2) it is not enough to increase urban public transport fleet solely, as the coefficient is less than 1 (i.e., 0.43), indicating a lack of elasticity; 3) the negative effects of private car ownership on public transport ridership is validated, but the quantity is larger for the eastern cities than that for the mid-west cities; 4) a spatial heterogeneity of urban public transport ridership is identified, to be specific, it’ s easier for the eastern cities to achieve a larger ridership volume, which we attribute to their advantage in more active social economical activities and higher transport supply per capita. The study would benefit ridership estimation for the targeted future year, and indicates the necessity of implementing different TDM policies across cities in different regions as well.

(2) As an important determinant of individual mode choice, public transport service quality is detailed into multiple items and measured from a passenger perspective. To be specific, service quality is the difference

between the expected and the subjectively perceived performance of each item, which is aggregated to an overall service quality after weighted with passenger rating importance. Empirical study is conducted confirming the applicability of the proposed methodology in measuring the route level public transport service quality and identifying the most negatively rated item.

(3) Taking passengers of the Beijing Subscription Bus Service as subjects, we have compared the utility composition change, including monetary cost, comfort, total travel time and travel time usage, before and after they shift from their previous commute mode. With survey data, significant improvement in travel time usage has been found for the respondents, whether they previously commute with private vehicle or public transport, and an acceptance of extra pay besides current fare for their improved travel time usage is also identified. Thus we could conclude confidently that measures helping passengers to spend their travel time effectively would benefit public transport with completion with individual mobility.

(4) A methodology is proposed to identify transfer activity and extract corresponding information from the smart card transaction records, together with GPS based bus trajectories and static geographic information of the bus network. Having conducted empirical study in Ningbo, China, we have validated the effectiveness of the method. With the extracted transfer information, we have drawn a profile on how the transfers distributed temporally and spatially with properly designed indicators. Entity (i.e., stop or route) pairs with extreme transfer/waiting time or walking distance have been identified and should be dealt with in order to improve the bus service.

(5) Based on household size, family member relationship and the presence of child, a concept of family life cycle stage (FLCS) is introduced to characterize households from an evolution perspective. With data of household travel survey in Yichang, we have formulated logistic regression models to depict the household automobile ownership, and the mode choice of family members, each with two specifications, one with the family lifecycle stage variable, while the other with multiple single indicators, e.g., household size (continuous), presence of child (binary). Comparison between two models on the same topic has validated the advantage of FLCS in better explaining data variation. Considering the behavioral implication of FLCS, we have compared the activity difference across FLCS and significant difference has been observed. Thus we have reached the conclusion that as the behavioral mechanism behind FLCS lies in the difference of activity needs.

(6) Though not directly observable, psychological factors are believed to influence individual travel decision. We have modeled how various norms constructs as well as other common socio-demographics affects travel behavior with sample data among Shanghai citizen. With a structural equation model integrating Theory of Planned Behavior (TPB) and Norm Activation Model (NAM), we have found that 1) high income doesn’ t necessarily cause low public transport use intention or actual usage, but its effect on mode choice is mediated by private car ownership. To be specific, higher income first associates with a higher private mobility ownership and then a lower public transport use intention; 2) people with perceived public transport pro norms (i.e., subjective social norms, descriptive norms or personal norms) are more likely to report a higher public transport use intention and actual usage; 3) an awareness of the negative effects by exceeding car usage would activate the personal norms to use public transport, while the effects of particulate matters and road congestion contribute more than social exclusion, individual health, energy crisis and traffic accident in activating personal norms.

Key Words:urban public transport, public transport ridership, public transport service quality, household auto ownership, socio-psychological factors