自动驾驶交通系统的协同管控技术

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摘要 过去10年自动驾驶技术的持续进步, 为交通系统的协同管控技术提升带来了巨大的机遇和挑战. 在微观层面, 自动驾驶车因其优于人类驾驶员的反应时间和对周边微环境的精准监控, 有望大幅提高道路通行能力, 减少事故发生率, 消除随机驾驶行为对系统稳定性和鲁棒性的影响. 在宏观层面, 交通系统管理者可以通过控制自动驾驶车的路径、车道, 乃至详细轨迹, 抑制拥堵的外部性, 减少甚至消除无效拥堵, 并以此为出发点指导下一代智慧公路系统的规划设计. 本文以此为纲, 总结了近年来自动驾驶交通系统协同管控技术领域的研究成果.

关键词 自动驾驶, 协同管控, 安全性, 鲁棒性, 智慧道路系统

高速公路系统是20世纪对人类社会影响最大的工程技术之一. 它通过立体交叉创造了全封闭、高效安全的驾驶环境, 极大地降低了居民出行成本, 提升了货物运输效率, 给全球物流和供应链带来了前所未有的变革. 2015年, 仅中美卡车货运总营收就接近万亿美元规模^[1], 高速路对全球经济的巨大作用可见一斑. 当前, 高速公路系统正在面临另一项技术的颠覆性冲击: 自动驾驶车(以下简称自动车, autonomous vehicles, AV)技术. 这项技术从20世纪80年代发端(如欧洲的普罗米修斯计划), 到2009年谷歌的无人车项目实现突破, 近年来受到世界各国政府、企业、学术界的广泛重视, 引领了整个交通运输行业的发展^[2-4]. 自动驾驶技术利用环境感知、自动控制 and 路径导航等技术实现自主行驶, 最终目标是将司机请出传统的“人-车-路”闭环控制系统. 目前, 美国多个州已允许自动驾驶实验车上路(<https://mobility21.cmu.edu/u-s-department-of-transportation-releases-policy-on-automated-vehicle-development/>).

欧洲多个国家开始规划自动驾驶车与传统车辆的混合交通系统^[5], 在无人工介入的情况下, 单车自主安全行驶的试验距离目前最高已达 1.78×10^4 km^[6]. 我国对自动驾驶技术的研究起步晚, 但进展迅速, 到2018年专用高速公路测试环境已开始出现(http://www.sohu.com/a/291692469_256868/), Apollo自动驾驶汽车已进入量产阶段(http://www.sohu.com/a/241389275_222256/).

自动驾驶技术的研究可追溯到20世纪^[7,8], 大体可分为两支. 一支主要关心车辆如何通过感知外界和实时判断, 生成并执行驾驶指令, 确保自主、安全地行驶; 另一支把关注点扩展到整个交通系统, 目标是对混合车队(包括自动车和传统车)的路径、车道乃至轨迹做精细的协同管理, 从而优化系统效率. 本文关注的研究领域集中在后者.

1 自动驾驶技术

为界定自动驾驶技术水平和发展阶段目标, 国际

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自动化工程师协会提出了自动驾驶分级标准^[9],包括人工驾驶(Level 0, L0)、辅助驾驶(Level 1, L1)、部分驾驶功能自主(Level 2, L2)、主要驾驶功能自主(Level 3, L3)、限制条件下自动驾驶(Level 4, L4)和完全自动驾驶(Level 5, L5)6个级别。每一个级别均从加减速及转向、驾驶环境监视、行驶模式下动态事件响应和全时全模式自动驾驶4个方面界定了相应的功能^[9]。迄今,全世界自动驾驶车测试平均行驶超过 5×10^6 km才有一次事故,超越了人类驾驶员平均每 3×10^6 km一次事故的安全可靠度。目前已有L3自动车在城市上路, L4自动车处于大规模测试中,包括百度、Google, Tesla, Pinyai, Uber等,少量在特定场景下的L4自动车进入量产阶段(http://www.sohu.com/a/241389275_222256/)。

随着自动驾驶技术软硬件层面的进步日新月异^[10],“如何把这项创新全面融入现有交通运行管控体系以提升机动能力和运输能力”这一问题开始进入交通学者的视线。自动驾驶为提升交通系统效率带来的机遇和挑战,来自宏观和微观两个层面。在宏观层面,交通系统管理者可以通过控制自动驾驶车的路径、车道,乃至详细轨迹,抑制拥堵的外部性,减少甚至消除无效拥堵,并以此为出发点指导下一代智慧公路系统的规划设计。在微观层面,自动驾驶车因其优于人类驾驶员的反应时间和对周边微环境的精准监控,有望大幅提高道路通行能力,减少事故发生率,消除随机驾驶行为对系统稳定性和鲁棒性的影响。下文从宏观和微观两个层面,对近年来国内外在自动驾驶交通系统的协同管控技术方面取得的研究成果做简要梳理。

2 宏观自动驾驶交通系统的协同管理

自动驾驶将出行者从驾驶任务中解放出来,赋予其自由时间来工作、学习或娱乐。诸多仿真试验发现这一优势也是一柄双刃剑。它一方面会降低出行成本,另一方面会催生更多的出行需求^[11~13],并延长出行者可接受的出行距离^[14,15],最终可能会恶化交通拥堵。从供给侧来看,自动驾驶有望增加道路通行能力^[16,17],且在商用普及之后易于实现共享共乘^[18,19],有望彻底变革私家车的拥车模式,大大降低车辆保有量^[20,21]。因此,未来自动车对城市拥堵的总效应取决于上述两种效应的共同作用。

自动驾驶的普及必然带来驾驶环境的变化,完全人工驾驶环境演化到混合驾驶环境,乃至演化到完全自动驾驶环境。混合驾驶环境是实现完全自动驾驶的

必经之路,该环境下的交通系统建模与管控技术已成为当今交通研究领域的热点。Levin和Boyles^[22]提出了基于元胞传输模型的动态交通分配模型,允许自动车和常规车共享道路。在此基础模型上,Duell等人^[23]与Levin和Boyles^[24]在时空两个维度上研究了动态可变车道的控制方法,Levin和Khami^[25]考虑了动态自动公交专用车道规划问题。Wang等人^[26]利用变分不等式建立了一个混合交通分配模型,定量地刻画了自动驾驶交通流和非自动驾驶交通流在网络上的均衡分布。Chen等人^[27,28]提出将部分交通基础设置改造为自动驾驶车专用设施可提高系统整体效率,前者考虑自动驾驶专用车道,后者研究自动驾驶专属区域。Zhang和Nie^[29]与Li等人^[30]分别从静态和动态角度研究了通过可控自动驾驶车辆之间的合作路径规划来实现路网整体效率的提升。

混合交通环境可能会加剧交通拥堵。Seo和Asakura^[31]提出了自动驾驶引起的“拥塞悖论”,即随着自动驾驶车辆渗透率的增加,道路实际通行能力呈现先降后升的趋势。“拥塞悖论”源于自动驾驶技术尚未完全成熟时,自动车与其他车辆间距的安全要求。Mehr和Horowitz^[32]也提出随着自动驾驶车辆渗透率的增加,系统总阻抗并不单调递减。Mehr和Horowitz^[33]通过算例说明了系统最优的道路收费方案需要对自动车和常规车区别对待。Roughgarden和Tardos^[34]证明了非自动驾驶下最差均衡效率(price of anarchy, PoA)是有界的,而Lazar等人^[35]通过算例说明了混合交通环境下PoA可能是无界的,并给出PoA有界的一个充分条件。假定自动车和常规车分别只能在各自所规划的区域行驶,而双模式车不受区域限制,Beirigo等人^[36]定量研究了混合交通环境对出行服务水平的影响。

研究者也开始考虑如何通过公共政策来促进自动驾驶与交通系统的协同发展,抑制自动驾驶的负面影响。Noruzoliaee等人^[37]刻画了自动车制造商、出行者以及基础设施规划者的决策行为之间的交互影响。Van den Berg和Verhoef^[38]分析了3种供应体制(公共供给,私人垄断以及完全竞争)下自动驾驶对出行行为的影响。Liu^[39]研究了自动驾驶对通勤者出发时刻和停车位置的影响。Loeb等人^[40]研究了基础设施建设(充电桩布局以及充电时间)。Simoni等人^[41]研究了不同拥堵定价方案(基于距离的定价方案、基于路段的边际成本定价方案以及基于行程时间的定价方案)对以共享自动车为主的未来运输系统的影响。Baron等人^[42]分析了

各种公共政策(购车退款、税收补贴以及自动车共乘协议)对自动驾驶车辆渗透率的影响。

自动驾驶给停车系统的运营管理带来了全新挑战。Kong等人研究了自动驾驶汽车泊车区车位的几何优化^[43],以及自动驾驶泊车与上下客活动对平面停车场的布局优化^[44]。Nourinejad等人^[45]和Timpner等人^[46]分析了自主泊车场景下,如何通过由中央系统调度的紧凑泊车、按需移动被泊车辆等手段,来提升停车场空间利用率。Kim等人^[47]分析了为缓解热点停车场压力,无载客自动驾驶使用远程停车场泊车对交通系统的影响。Childress等人^[48]开展了自动驾驶对停车成本影响的分析。

3 微观自动驾驶交通系统的协同控制

传统驾驶模式下,管理拥堵外部性、实现系统最优主要通过影响宏观出行行为(例如出行方式、出发时间以及路径)来实现。更微观层面的控制,包括路径选择、改变车道、跟车距离等,则由于系统无法提供实时控制而只能忽略。在纯自动车环境下,理论上可以通过提供任意时空粒度的行驶方案,优化整体交通系统效率。“虚拟轨道”为实现这一理论蓝图提供了思路,即在高精地图^[49]导航场景下,将纯自动驾驶控制方式与铁路系统的“集中调度”方式^[50]类比,把自动车辆行驶车道作为虚拟的列车轨道看待(图1)。相应地,车辆轨迹优化如同铁路车站咽喉区的“进路冲突优化”(图2)。成熟的铁路系统列车群控制方式和安全保障原则为自动驾驶中央交通控制模式提供了可靠的技术基础。

虽然自动驾驶“虚拟轨道”交通管控系统与轨道交通系统的控制机理趋于一致,但是自动车换道行为任意、空间维度的连续性给数学建模带来了巨大的技术难度^[50-53]。Lu等人^[53]利用沿道路纵向空间连续、车道和时间离散的变量体系,有效解决了车辆变道点分布的随机性特点,使用与铁路车站咽喉区冲突优化建模类似的思路,建立了自动车轨迹优化及换道决策模型,以保证自动车队系统运行整体最优。该模型可方便、准确地对路段内部分车道封锁、匝道汇入与分流等典型公路场景开展应用。另一种思路是将空间与时间离散化,建立时空网络模型^[52],在离散三维坐标系中布置类似于铁路用于变换列车轨道的虚拟道岔,从而寻找自动车最优轨迹。由于空间离散,该方法处理车辆换道行为需在预定的虚拟道岔处进行。

基于“虚拟轨道”的全网控制模式需跟踪系统内所有车辆轨迹,虽然潜力巨大,但对计算资源和速度的要求很高。另一个思路是放弃对单个车辆轨迹的控制,转而对自动驾驶车辆编队行进开展控制,类似列车的“移动闭塞”控制方式^[54-56]。编队行驶的优势是大型自动车之间形成“气流真空区”,可以有效降低空气阻力,减少燃油消耗和排放^[57]。自动车编队行驶试验目前主要在物流和货运各种封闭场景(如港口码头、仓库、工厂等)中开展^[58-60]。编队控制涉及的一个关键问题是车队运行的稳定性问题,避免系统状态的扰动向车队上传传播、放大导致交通拥堵(如stop-and-go)^[61,62]。自动车编队的稳定性研究主要分为两大类:第一类是从系统

图1 高精地图及虚拟轨道示意图(<https://erticonetwork.com>)

Figure 1 Illustration of virtual track on a high-precision map (<https://erticonetwork.com>)

图2 列车轨道进路与自动驾驶虚拟轨道示意图。(a) 铁路车站咽喉区; (b) 交叉口及自动驾驶虚拟轨道

Figure 2 Comparison of conventional train track and virtual track used by AV. (a) Bottleneck of railway station; (b) virtual track used by AV in a road intersection

控制理论的角度来研究队列稳定性(string stability); 第二类是交通流理论结合车辆运动学研究交通流震荡(traffic oscillation)问题。前者通过稳定性分析方法(如李雅普诺夫、时间域、Z-域、s-域、图论等)得到稳定性的充分条件, 设计满足稳定性充分条件的控制器^[63-69]。后者构建自动驾驶运行轨迹规划模型与算法^[70,71], 降低交通流系统的震荡。由于人类驾驶行为的随机特性, 传统车队往往队列是不稳定的^[72-74]。对混合交通流的稳定性研究也可分为两大类: 第一类是利用系统控制理论或仿真方法研究混合队列稳定性, 如Zhou等人^[75]通过最大化“头-尾”稳定的子队列数量, 提高整个混合车流系统的稳定性。Talebpour和Mahmassani^[76]通过仿真分析了自动驾驶联网程度、渗透率对混合车流队列稳定性的影响。第二类是考虑单个自动驾驶或多个随机位置的自动驾驶对混合车流稳定性的影响, 研究方法涉及理论分析^[77]、建模仿真^[78]和真实场景测试^[70]等, 以及通过优化控制自动驾驶轨迹, 提高混合车流系统稳定性, 减少交通震荡^[71]。

自动驾驶换道问题有特殊的复杂性和重要性, 近年来研究大致分为自由换道和强制换道两类。前者包括面向复杂城市路况的仿生换道决策^[79], 考虑自动驾驶联网的分散式协调换道决策^[80], 用于超车换道决策的混合逻辑动态系统^[81]和多目标强化学习框架^[82]。后者的核心思路是实现微观换道决策与宏观路径规划一体化的建模目标, 如自动驾驶强制换道的最优决策点^[83]、自动驾驶车强制换道行为选择与路网行驶效率的函数关系^[84]等。

交叉口控制技术对自动驾驶的适应^[85], 主要有3条途径: 第一是基于信号灯控制机理, 利用联网汽车的信息动态优化信号灯配时^[86,87]; 第二是通过交叉口控制器对自动驾驶的进入请求设置不同放行规则^[88,89]; 第三种方式则摒弃传统地面交通控制手段, 直接对每个自动驾驶的轨迹实施控制, 保证安全, 提升效率。该方式可通过网联自动驾驶信息交互与驾驶行为优化方法实现^[90], 也可以通过交叉口轨迹集中控制与优化的方法实现^[91], 其轨迹决策均以“虚拟轨道”概念为基础。交通管理对交叉口通行效率的优化, 常见的目标包括缩短交叉口车辆的总通行时间^[88]、最小化交叉口车辆总延迟^[92]等。优化的方法包括车辆的进出交叉口时间优化^[92,93]、车辆时空轨迹相互覆盖最小^[94]、优化车辆的加减速策略^[91]、车辆时空轨迹与信号灯联合控制^[95]等。虽然初步研究显示自动驾驶交叉口的通行效率与传统信号灯交叉口相比大幅提升^[94,96], 但绝对的安全保障原则对效率的影响仍不明朗。

4 总结与展望

自动驾驶技术以智能的交通行为感知、判断、决策与执行能力形成脱离人类驾驶员的新型驾驶模式, 是地面出行方式的重大变革, 也是人工智能科技领域群雄逐鹿的重要战场。在车车通信、车路通信和高精度地图等技术的辅助下, 这一技术正在催生全新的协同交通管理与控制方法, 打造下一代智慧公路系统的大脑, 为创造安全、高效、环保、经济的交通运输系统奠定基础。

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Summary for “自动驾驶交通系统的协同管控技术”

Coordinated management and control of autonomous traffic systems

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The rapid development of autonomous driving technology in the past decade has brought unprecedented opportunities and challenges to the coordinated management and control of traffic systems. Compared to human drivers, autonomous vehicles (AV) are equipped with shorter reaction time and better situational awareness, promising to increase the throughput of existing road networks, dramatically improve safety and robustness, and reduce the instability of vehicular traffic flow. Moreover, controlling the route, lane and even trajectory of every AV in a network could effectively eliminate excessive congestion caused by “selfish” human travel and driving behaviors. This ability to coordinate the entire AV fleet thus has important implications for planning the next-generation “smart” road systems.

In this paper we consider the coordinated management and control of AV fleets from both macroscopic and microscopic perspectives. The former focuses on how coordinating macroscopic travel decisions, such as route, departure time and mode (e.g., ridesharing vs. micro-transit), might help reduce traffic congestion caused by what is widely known as the price of anarchy in transportation. While the underlying idea is simply moving the system from a user equilibrium state to a system optimal one, the challenge is to model the complex interactions between autonomous and human-driven vehicles, to anticipate how human drivers would behave in such an environment, and to design effective, fair and practical schemes to achieve the goal. What we learn from these efforts could potentially impact infrastructure planning, especially in terms of whether and how AVs should be separated from human-driven vehicles on road.

On the other hand, because AVs can be programmed to remember and execute all maneuvers in a journey, much like the auto pilot for airplanes and high-speed trains, the entire trajectory of their journey, not just the aforementioned macroscopic travel decisions, may be targeted for the purpose of traffic management. Here, the focus is to manage the microscopic maneuvers (e.g., lane changing and gap-keeping behaviors) of a fleet of AVs to improve the performance of the road network. An interesting analogy can be drawn between this task and the task of managing a railway network in which many fast moving trains operate. Accordingly, the lanes on highways may be viewed as “virtual tracks” in an imaginary railway network. There is an extensive literature on railway operations from which one can draw useful mathematical tools and empirical results. A primary challenge to operationalize this analogy is the enormous computational requirement caused by both the sheer size of the problem, as well as the short time framework (seconds or shorter) within which such a coordinated management and control decision must be made.

autonomous driving, coordinated management and control, safety, robustness, smart road systems

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