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从数据挖掘到智能调度决策支持：存在问题与实施路径

Ingo A. HANSEN

（代尔夫特理工大学，荷兰 代尔夫特 2628CD）

摘　要：铁路运营决策复杂度的不断提升要求开发和运用实时智能列车调度决策支持工具.首先分析了开发智能决策支持工具的问题和主要障碍.其次阐述了计算机系统对辅助列车运行图编制和运行调整等任务的作用，其中详细分析了通过先进的统计分析工具和机器学习对运营大数据进行挖掘的方法，并说明数据挖掘可以对列车速度、正点率、能力、能耗进行较为详细精确刻画和预测；另外，阐述了铁路列车时空分布的精确建模对编制和实施具有鲁棒性的列车运行图的重要性，以及基于有效决策支持的实时调度指挥辅助系统的发展进程.最后，对在主要铁路线路和区域铁路线路上运用先进的列车运行控制和安全信号系统的全自动或半自动列车驾驶的可能性进行了论述.

关键词：智能调度；列车控制；铁路大数据；数据挖掘；鲁棒性时刻表

中图分类号：U293.1　　**文献标志码**：A

Closing the loop between data mining and fast decision support for intelligent train scheduling and traffic control

Ingo A. HANSEN

(Delft University of Technology, Delft 2628CD, the Netherlands)

Abstract: The existing Big Data of transport flows and railway operations can be mined through advanced statistical analysis and machine learning methods in order to describe and predict well the train speed, punctuality, track capacity and energy consumption. The accurate modelling of the real spatial and temporal distribution of line and network transport, traffic and performance stimulates a faster construction and implementation of robust and resilient timetables, as well as the development of efficient decision support tools for real-time rescheduling of train schedules. In combination with advanced train control and safety systems even (semi-) automatic piloting of trains on main and regional railway lines will become feasible in near future.

Keywords: intelligent train rescheduling; train control; big railway data; statistical learning; robust timetabling

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第一作者：Ingo A. HANSEN(1946—)，男，德国人，教授，博士.研究方向为铁路运输组织优化.**email**：i.a.hansen@tudelft.nl.

通信作者：孟令云(1983—)，男，河北唐山人，副教授，博士.**email**：lymeng@bjtu.edu.cn.

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万方数据

1　介绍

铁路企业每天都会收集和保存大量实际运营中产生的数据，其中包括铁路旅客、货物和列车的数量、起点以及目的地.同时，信号机、轨道电路、计轴器、联锁、闭塞分区、变电站和机载单元自动生成和传输关于铁路基础设施、轨道占用和机车车辆的数十亿条信息.数据通过过滤和选择，广泛应用于开行方案、时刻表、交通控制、故障/事故检测和维修计划，以确保列车安全、准时、高效的运营，并提供可靠的客户和管理信息.

新信息的巨大规模和生成速度要求铁路员工很好地理解和运用数据处理、储存和分析工具.首先需要明确现阶段哪种数据与列车智能调度、运营管理、客户信息相关？最重要的是，必须确保与安全相关的重要数据的实时收集和交互，以便调度人员在必要时能够迅速做出适当的决定.这意味着任何影响列车实时检测、线路联锁、行车间隔计算、列车控制和调度权限的信号和安全系统数据都是至关重要的.而一些非安全数据可稍后或待运营结束后进行数据分析与传输，其中包括：常规的客货流信息、列车延误记录或商业广告等.

然而，列车驾驶员、调度员和运营管理人员在信息识别、评价/决策可靠性、信息处理的速度及能力是有限的.根据行车密度和列车速度、实际运营条件（天气、能见度、噪音）、信息清晰度、操作人员任务的复杂性以及个人专业经验、列车驾驶员的反应时间以及交通或信号控制器间的差异很大.一般来说，如果信号将在几秒钟内变成黄色或红色，一位训练有素的列车驾驶员会适时进行制动操作.对列车驾驶员、调度员或运营管理人员的工作负荷和决策时间进行人体工程学和实证研究的文献仍然较为缺乏[1-2].

开发和运用实时列车调度的智能决策支持工具的主要障碍是：

1）对于重要的信号安全系统和非重要的决策支持系统（用于计划、调度和驾驶员）之间的明确区分和快速高效的信息传输；

2）对具有鲁棒性、准确性、计算/通讯时间较短的实时调度和驾驶员辅助决策工具提出更高要求；

3）对日常运营中的不足以及用户反馈记录的不充分；

4）缺少清晰和简单易懂的用户界面及其输出；

5）利益相关者在政治、经济、社会上的利益不同；

下文的主要目的是简要说明如何通过更有效的计算机决策支持系统执行一些复杂的列车运行图编制和运行调整交通管理等任务.

2　计算机辅助决策支持方法

2.1　统计学基础

基于自动生成的列车检测、信号、安全系统数据（轨道占用/出清，信号，进路建立，路径设置/解锁、移动权限），可以监控和分析主要列车的运行，例如运行时分、安全间隔时间、停站时间、到达时刻、离开时刻、延误时间.

在过去，几乎只有在时刻表发生变化时，计划的列车运营时间才会进行更新，采用新的动车组或通过简单地增加运营时间被证明是不可行的.相反，应该定期对主要列车运行时间的分布情况进行分析，以便估计运行时间的统计拟合和标准参数，这些参数可用于评估时刻表的质量和列车运行性能，并使时刻表更精确地贴近实际的列车运行时间.另外，运行时间和停站时间的概率分布一般是右倾斜的，主要是因为运行计划的缓冲时间、列车安全间隔时间以及路径的冲突.到达延误时间似乎符合对数正态分布和伽玛分布，而发车延误时间可用负指数、威布尔、伽玛密度分布进行描述[3].

列车运行时间的在线预测需要使用复杂的统计学习方法.已在本地和全球范围内分别测试了多元线性回归（MLR）、回归树（RT）和随机森林（RF）模型，以估计运行时间和停站时间[4].局部模型描述了同一线路列车在特定路段上运行时间的变化，而全局模型将记录所有列车的处理时间，并分别聚合为两个分离的测试集，分别测试运行时间和停站时间.由于前车或线路冲突而受阻的列车的处理时间已被过滤掉，因此数据集中只包括无冲突的运行时间.由于模型必须对异常值具有鲁棒性，因此相较于可能对数据过度匹配且差异较高的模型，能够处理异常值的模型更受青睐.在预测精度方面，预测模型对于运行时间的预测准确率明显低于停站时间，因为停站时间往往只因列车延误而受到微弱影响，而到达延误时间和高平峰时段之间的客流量变化会对运行时间产生较大影响.此外全局模型的预测精度也明显低于局部模型.比较不同模型的精确度可以发现，用于鲁棒线性回归的最小修正方法（LTS）优于 RF，在运行时间和停站时间的预测上都优于 RT 模型.

2.2　具有鲁棒性的时刻表

时刻表编制主要可分为图形化、分析、仿真模型和组合优化 4 种方法.

万方数据

1)图形化的时刻表编制模型,例如计划列车的时间-距离图描述了列车在车站的到达时间和发车时间、站台股道的占用时间等,是描述列车运行计划和轨道基础设施使用情况的标准方法,一般在宏观层面使用(分钟,千米).列车时间-距离图还用于根据预期的运输需求(列车发车频率和速度)及每条线路所需的(最小)安全间隔时间,快速检查时刻表的可行性.然而宏观图形化时刻表模型的离散化步骤太大,无法准确描述有关技术和安全的约束,例如轨道校准、信号、联锁和列车牵引制动性能对线路能力的影响[5].

2)到目前为止,铁路时刻表主要是基于车站之间确定的运行时间、停站时间和安全间隔时间来制定的.服务时间的微小变化可通过运行时间和停站时间的冗余时间及列车路径之间的边界(缓冲时间)进行补偿.在实际应用中,冗余时间和缓冲时间的确定主要是基于经验法则,有时也通过仿真进行验证.排队模型能够估计时刻表的列车等待时间,以此作为轨道占用函数及个别线路和简单车站的行车间隔和服务时间的变化系数.而具有多个轨道和路线的主要车站通常以多服务台排队系统进行建模.但是,随机分布函数的类型、性质和参数通过对实际运营数据的统计分析进行验证[6-7].时刻表的随机变量产生的计划等待时间必须与运营期间的预计初始延误和二次延误区分出来.特别是在利用率高的路网中,因为信号系统和安全系统在追踪间隔和路线冲突时的实际列车速度和服务时间大多是未知的,这可能会低估延误时间的传播.事实上,车站到达时间和服务时间的安全间隔时间分布存在着随机相互依赖的关系.

3)用于估计不同列车运行时间和停站时间的宏观仿真模型无法准确估计特定技术操作规则的影响,如不同的信号和安全系统、闭塞分区信号间距、局部速度限制、信号和路线的联锁、列车长度、减速度和加速度、(最小)安全间隔时间及车站区域的延误时间.在最糟糕的情况下,因为列车延误在制定时刻表的时候被低估,较紧的列车时刻表甚至可能变得不可行.这就是为什么几个欧洲铁路运营公司开发和实施微观时刻表模拟模型的原因[8].安全间隔、路径冲突、线路能力的使用及初始延误和二次延误的传播是根据秒和米范围内的轨道区段锁闭时间图来计算,因此比以前精确 60 倍[9].

4)组合优化模型旨在解决公式化的时刻表优化问题,模型具有特定目标函数且有一定的约束,以此优化生成网络中列车在车站的到发时刻计划.模型一般是混合整数线性规划模型,并运用商业优化求解软件进行求解;模型如果难以用商业求解软件进行求解,则会通过启发式方法进行求解,例如分枝定界法或拉格朗日松弛等.在求解列车时刻表时,若模型的路网数据范围超过计算内存或求解速度过慢时,一般会采用混合优化方法,它集成了宏观全局网络时刻表优化和局部/区域网络的微观仿真[10-11].通常情况下,在给定约束如最小的安全间隔时间和列车之间的传输时间优化模型,应用确定性变量来搜索目标函数的(临近)最优解,以最大限度地减少网络中的总运行时间,但该模型在一定程度上具有局限性.在多股道的车站无冲突列车线路上,规定的列车运行时间和最小安全间隔时间的可行性往往没有得到证明,因为确切的轨道占用、规模、分布和对时刻表松弛的使用情况仍不明确.豁免(exemption)是最近兴起的一种迭代方法,用于从零开始在复杂的车站区域构建一个创新的无冲突和具有鲁棒性的乘客路径计划和微观时刻表,以此对缓冲时间进行智能分配[12].但是,运行时间和行车安全间隔时间仍被视为时刻表的给定输入,列车速度也没有进行优化.大多数学模型都缺少以标准时间距离、速度距离和进度时间分布等形式评价列车时刻表的基本图,这是在实际应用中对其进行测试的一个重要障碍.

2.3 实时调度

由于现有的在运行时间添加缓冲时间的方法(在最小运行时分之外加入至少 3%的缓冲时间),在列车延误时间较小的情况下(1~2 min),列车会自动恢复至正点运行,并且时刻表中提供的缓冲时间(至少 1 min)可以避免或减少列车二次延误.但是,由技术故障引起的个别列车产生的较大延误时间可能会对时刻表造成较大的影响,即导致列车运营至少在一个方向上中断且持续时间超过 1 h.实时调度模型可以帮助调度员和运营管理人员快速识别和解决路径冲突.经常发生在咽喉区和车站的列车延误,调度员根据经验可以通过简单的调度措施(等待、更换股道、改变列车运行次序、取消车次)进行处理.但由于技术故障、非常恶劣的天气或事故造成的重大中断应由运营管理人员运用(静态)应急计划进行处理.在开行密度较高的线路上,尤其是在单线铁路上,每一次运营中断都会大大降低线路通过能力,因此取消一些列车服务是不可避免的.调度决策的效率可能不是最优的,因为它们只通过无线通信和有限的视觉网络事故信息进行决策,无法很好地预测其调度措施对局部地区和区域网络列车运营的影响.

万方数据

在过去十年中，开发了一些计算机实时调度工具为列车运营受扰动的线路或网络快速生成相对(次优)最优的时刻表[13-20].实时调度模型需要解决以下问题：

1)信号、安全、交通控制和联锁系统的数据加载和通信；

2)列车路径规划；

3)潜在行车安全间隔和路径冲突的检测和疏解；

4)确定路网边界、中间站、相关的信号机、交叉点、交叉口的确切到发时刻；

5)列车速度曲线的调整.

时至今日，这些工具都没有与铁路企业的数据处理器和铁路运营管理企业进行实时连接、沟通和测试.所有工具都必须编译以前保存的日志文件副本作为测试的输入数据，其中包含列车时刻表、信号机和联锁等相关信息.模型输出至今都是在实验室里进行离线计算的，因为铁路运营公司至今还在犹豫是否要测试并验证实时调度工具在实际运营中的有效性.这意味着，在发生事故时，智能调度系统提供的调度方案和调整后的实际运营情况无法实时向运营管理人员进行展示，因此也无法将调度系统优化的方案与调度员作出的决策进行比较.

值得一提的是，科研人员提出的一个创新的调度方案闭环优化框架，已在英国、荷兰、瑞典、挪威这4个国家铁路网络中进行了案例研究.该框架可以基于列车运行预测数据，在指定的调度范围内，实时得出最优的调度计划，并通过人机界面呈现给调度员.如果调度员接受该调度计划，自动路径设置模块会自动实施该调度计划，即通过为列车设置最优的路径，并将列车运行速度建议传输至驾驶员辅助系统以实现节能驾驶.两种不同的冲突检测疏解模块(ROMA和RECIFC)在挪威和瑞典被提出，并在铁矿线上进行仿真，以比较其性能.

现有的路径更改和时刻表变更的调度模型在处理扰动或部分轨道封锁的情况下根据以下因素进行区分：扰动范围(往往限于联锁区域内的几条标准(通过)路径)、离散化程度(宏观/中观/微观路网模型；列车长度；时间步长(位置、速度、加速度、减速度))、离散事件或同步计算的轨道占用时间、出清时间、联锁时间、安全间隔时间和相应的锁闭时间.应用数学规划方法针对铁路线路和安全间隔的冲突检测有以下研究：可替代图(基于列车速度可协调的车间作业模型)[14-16]；双层资源树冲突图[17]；在闭塞分区入口有速度变化的资源集合配置[18]；没有速度变化的混合整数线性模型(Pellegrini).一般情况下，需要启发式算法来解决短时间内(1～2 min)的调度问题.实时调度模型的首选目标可能是尽量减少①(最大)连续列车延误，②连续的乘客延误，③ 有优先级的列车总延误.最小化列车运行的总延误时间也会被用作目标函数.但是，总延误时间会受初始延误情况的影响，它与应用何种调度工具无关，但或多或少会减少二次延误.

2.4　驾驶辅助系统

驾驶员不能精确地预测准确的最早/最晚的惰行时间或者制动时间，因此驾驶员也不能实现最优的节能驾驶策略及绝对的按图行车.另外，只有训练有素、经验丰富的驾驶员才知道该趟车次可用的缓冲时间，在列车运营受到小扰动的情况下，会运用缓冲时间恢复正点运行.目前的列车驾驶辅助系统(DAS)，如果基于列车超速防护(ATP)和列车自动控制(ATC)系统之上，则可以告知驾驶员实际列车延误时间(以分钟为计)和列车速度建议，而不考虑实际列车延误和网络拥堵的影响.欧洲、北美、日本的一些城市轨道交通系统在列车上装备了一种自动巡航控制(ACC)系统，该系统根据列车的标准速度曲线、行驶距离、牵引力/制动力、需要的安全间隔时间，可以持续控制单列车的加速度、实际速度和减速度.

智能驾驶辅助系统可以使用信号和安全系统实时生成的交通信息，信息可以通过无线闭塞中心(RBC)传送到调度中心.为驾驶员提供灵活的列车速度建议是很有必要的，尤其是在高异质性、停站方案多变的高密度铁路线路上，以及在极端天气和有重载货车的情况下.调度中心可以将建议速度信息传输至列车车载单元，以避免列车间的冲突并尽可能使列车进行节能驾驶.DAS系统架构分为中央、中间、车载三种形式，不同形式的选择取决于速度曲线和速度建议重新计算地点的不同[21].智能算法在以下几个方面的发展是较为具有挑战性但是具有实际意义的：①实时预测列车运营时间；②根据最优速度曲线实时计算和传输速度建议信息；③在区间和车站区域的智能调度[22-25].DAS系统可以确保无冲突的列车运行，减少列车延误，提高列车服务的准时性并实现列车节能驾驶.提供的建议速度信息不是必须遵循的，如果发生超速、列车运行间隔时间或路径冲突，ATP / ATC系统会推翻该速度建议信息并保证列车安全运行.

3　结论

如果基础设施的能力、列车服务的质量、实时运

营信息的准确性和可靠性得到提高，那么铁路的吸引力、运输量、市场份额将会相应地提高.这可以通过将大数据挖掘和机器学习一体化的方法来实现，大数据挖掘可以通过共享数据(包括运输、技术、运营、安全数据、业务数据)和开发先进的统计分析工具来进行，这可以更好地描述和预测实际列车速度、准时性、能力和列车运行能耗.对线路、局部网络、区域网络、国家铁路网络的铁路运输、运营、性能的时空分布进行进一步的研究，可以促进鲁棒性时刻表的发展、测试、和更快的实施.同时采用高效的决策支持工具对列车时刻表进行实时调整，可以最大限度地减少运营中断对铁路能力和服务质量的影响.专用的铁路基础设施、高性能的列车控制和安全系统有利于列车在干线上进行自动驾驶[26].

在列车运行受到扰动的情况下，快速制定最优调度计划的最大障碍不是技术或计算能力对的限制，而是目前时刻表制定人员、驾驶员、调度员的能力限制，以及由于基础建设公司和运营公司的分离造成的组织障碍.在驾驶和调度上的人为不足可以通过给予信息、培训和激励来提高，但组织障碍需要基于社会目标和不是商业目标的政治干预才能化解.

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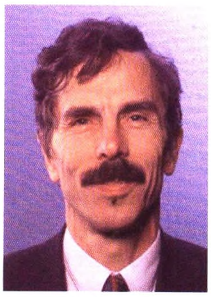
(孟令云　译)



英戈·汉森，曾任代尔夫特理工大学土木工程与地球科学学院运输及规划学系的运输设施设计教授，国际铁路运营管理协会(IAROR)主席.现任北京交通大学交通运输学院及中国铁路科学院客座教授，IAROR 副主席并组织协办铁路运营模型和分析会议.目前是《轨道交通规划与管理》(JRTPM)杂志主编、编委，交通运输研究委员会 Part B 和铁路工程学会的编辑顾问，多家交通类期刊如 Transportation Research Part C、Institnte of Electrical and Electronics Engineers 及 Journal of Advanced Transportation 客座审稿人.出版著作有《列车运行图与调度指挥》(2008)《列车运行图编制与运营管理》(2014)，并发表论文 100 余篇.

孟令云，北京交通大学交通运输学院副院长，曾主持国家自然科学基金重大项目“复杂环境下高速列车运行优化控制方法－3(协同优化方法)”、国家重点研发计划“在途运行智能调度技术研究”、国家自然科学基金面上项目“高速铁路调度指挥计划同步优化模型和算法”、国家重点实验室“基于可变轨道区段锁闭时间的列车运行计划优化编制方法”等多项国家级及省部级科研项目，多年来从事列车运行图编制和调度指挥计划优化等方面的研究工作，担任国际铁路运营管理研究协会委员一职，在 Transportation Research Part B 等国际期刊发表论文 20 余篇，担任多个国际著名期刊的审稿人.

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附录

Closing the loop between data mining and fast decision support for intelligent train scheduling and traffic control

Ingo A. HANSEN

(Delft University of Technology, Delft 2628CD, the Netherlands)

Abstract: The existing Big Data of transport flows and railway operations can be mined through advanced statistical analysis and machine learning methods in order to describe and predict well the train speed, punctuality, track capacity and energy consumption. The accurate modelling of the real spatial and temporal distribution of line and network transport, traffic and performance stimulates a faster construction and implementation of robust and resilient timetables, as well as the development of efficient decision support tools for real-time rescheduling of train schedules. In combination with advanced train control and safety systems even (semi-) automatic piloting of trains on main and regional railway lines will become feasible in near future.

Keywords: intelligent train rescheduling; train control; big railway data; statistical learning; robust timetabling

1 Introduction

Every day, a huge amount of data on the actual transport flows containing the number, origin and destination of railway passengers, cargo and trains is collected and saved by railway undertakings. Simultaneously, signals, track circuits, axle counters, interlocking machines, radio block centres, substations and on-board units generate and communicate automatically billions of real-time messages on the actual occupation of the railway infrastructure and rolling stock, respectively. The digital data is filtered, selected and used for line planning, timetabling, traffic control, failure, incident/accident detection and maintenance scheduling in order to ensure safe, punctual and efficient train operation, as well as reliable customer and management information.

The enormous size and speed of new information requires very powerful data processing, storage and analysis tools to be understood and handled well by the railway personnel and staff. Which kind of data is now relevant for intelligent train scheduling, traffic management and customer information? Above all, the compilation and communication of safety-related vital data must be assured so that the responsible staff members can take appropriate decisions quickly, if necessary. This means any signalling and safety system data affecting thereal-time train detection, safe route interlocking, headway calculation, train control and movement authority are crucial. Non-vital data, as regular passenger and cargo flow information, train delay records or commercial advertisement may be transmitted later on and analysed off-line.

However, the capability, reliability and speed of on-line information recognition, evaluation and decision making of the railway personnel involved in train driving, scheduling and traffic control is limited. Depending on the traffic density and trains' speed, actual environmental conditions (weather, visibility, noise), clarity of the information, complexity of the operator's task, and personal professional experience the reaction time of train drivers and traffic/signal controllers varies considerably. In general, a well-trained driver of a conventional train is expected to start braking if a signal aspect changes to yellow or red within a few seconds. Ergonomic and empirical research on the work load and the time to take a decision of train drivers and railway dispatchers/traffic controllers, respectively is still very rare[1-2].

The main barriers for a successful development and implementation of intelligent decision support tools for real-time train scheduling and traffic control are:

1) Clear distinction and fast reliable data transmission between vital signalling & safety systems and non-vital decision support systems for planning, dispatching and train driving;

2) High robustness, accuracy, computation and communication speed of real-time rescheduling and driver advisory tools;

3) Insufficient performance evidence and end user acceptance in daily practice;

4) Missing clarity and easy understanding of the user interface and output;

5) Diverging political, business and social interests of stakeholders.

The objective of the following section is to describe briefly, how some complex and routine human tasks for timetabling, train dispatching and traffic management can be performed through more efficient computerized decision support systems.

2 Promising computerized decision support approaches

2.1 Statistical learning

Principal train operations times, such as running/headway/dwell/arrival/departure/delay times, can be monitored and analysed rather easily based on automatically generated train detection, signalling and safety system data (track occupation/clearance, signals, switches, route set-up/release, movement authority). Updating of scheduled process times was done in the past mostly only when timetables changed, new rolling stock was employed or obviously proved infeasible by simply increasing the scheduled times here and there. Instead, the distributions of the main train operations times should be analysed regularly offline in order to estimate their statistical fitting and standard parameters that may be used for the ex-post evaluation of timetable quality and train operations performance, as well as for a consistent, more accurate adaptation of the scheduled train operations times. By the way, the probability distribution of running times and dwell times are generally right-skewed due to scheduled supplements and possible headway and route conflicts. Arrival delays seem to fit lognormal and gamma distributions, while departure delays fit well to negative exponential, Weibullor gamma density distributions[3].

Online prediction of train operation times requires the use of sophisticated statistical learning methods. For this purpose Multiple Linear Regression (MLR), Regression Tree (RT), and Random Forest (RF) models have been tested for the estimation of running times and dwell times, respectively, on a local and a global level[4]. The local model described the variation of running times of trains of the same line over a particular lock section, while the global model aggregated the process times of all recorded trains into two separated test sets for running times and dwell times, respectively. The process times of the trains which had been hindered by preceding trains or route conflicts have been filtered out, so that only conflict-free running times have been included in the data set. As the models must be robust against outliers, models that can cope with errors are favoured compared to models with high variance that may overfit the data. The prediction accuracy of the trained models for running times was significantly less than for dwell times, because the former depend only weakly from train delays, while arrival delays and variation of passenger volume between peak and off-peak periods impact strongly on the latter. The prediction error of the global models was clearly higher than of the local models. Comparing the accuracy of the different methods, the least-trimmed squares (LTS) method for robust linear regression outperformed the RM model and even more clearly the RT model for, both, running time and dwell time.

2.2 Robust timetabling

Four main approaches for timetabling can be distinguished: graphical, analytical, simulation models, and combinatorial optimization models.

1) Graphical timetable models like time-distance diagrams of scheduled train arrival and departure times at stations and platform track occupation times are standard means to illustrate the planned movement of trains and the use of track infrastructure generally at macroscopic scale (minutes, kilometres). Train diagrams are also used to examine quickly the timetable feasibility based on the expected transport demand (train frequency and speed) and required (minimum) headway times on each line. However, the discretisation steps of macroscopic graphical timetable models are too big for describing accurately the impact of technical and safety constraints concerning track alignment, signalling, interlocking and train dynamics on track capacity[5].

2)So far, railway timetables are based principally on deterministic running, dwell and headway times between stations. Small variations of the service times are compensated by standard running time and dwell time supplements, as well as margins (buffer times) between the train paths. The determination of supplements and buffer times in practice is mainly based on rules of thumb, sometimes validated by simulation. Queuing models enable to estimate the waiting time of a timetable as a function of track occupancy and the coefficients of variation of the scheduled headway and service times of individual lines and simple stations. Major stations with multiple tracks and routes may be modelled as multi-channel service systems. However, the type, properties and parameters of the distributions of stochastic analytical models need to be validated by means of statistical analysis of real-world operations data[6-7]. Scheduled waiting times generated by stochastic variables of the timetable must be clearly distinguished from estimated original and consecutive delays during operations. In particular on densely occupied, strongly interconnected networks this may lead to underestimation of the delay propagation, because the real train speed and service time of the signaling and safety systems at headway and route conflicts are mostly unknown. The distributions of headway times at arrivals and service times in stations, in fact, are stochastically interdependent.

3)Macroscopic simulation models used for the estimation of varying train trip and dwell times cannot estimate accurately the impact of specific rules of operation, different signalling and safety systems, block signal spacing, local speed restrictions, interlocking of signals and routes, train length, braking and acceleration, (minimum) headway times, and delays experienced in station areas. In the worst case, tight train schedules might even become infeasible and train delays, in fact, would be underestimated. That is why microscopic timetable simulation models have been developed and implemented in several European railway networks and countries[8]. Headway and route conflicts, use of track capacity and the propagation of primary and consecutive delays are computed on the basis of so called blocking time diagrams at a scale of seconds and metres, thus being 60 times more precise than before[9].

4) Combinatorial optimization models aim at solving the formulated (timetable) problem for a certain objective function under predefined constraints to optimality and, thus, generating an optimal design for individual train departure and arrival times in a network. They are computed via (Mixed) Integer Linear Programming ((M)ILP) by means of a general-purpose solver or, if intractable, by heuristic methods using e.g. Branch-and-Bound or Lagrangian relaxation. When the scope of the investigated railway network and data exceeds the computation memory and speed for solving the timetable problem a hybrid optimisation approach integrating macroscopic global network timetable optimisation and microscopic simulation of local/regional networks offers a loophole[10-11]. In general, optimisation models apply deterministic variables for searching the (near) optimal value of the objective function as minimisation of overall

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running times in networks at given constraints like minimum headway and transfer times between train are also validated insufficiently. The feasibility of the given scheduled train running times and minimum headway times is often not proven with respect to conflict-free train routing in multi-track stations, while the exact track occupation, size, allocation and use of timetable slack remains unknown. An exemption is the recent iterative approach for constructing an innovative conflict-free and passenger robust routing plan and microscopic timetable for complex railway station areas from scratch, which enables a smart allocation of buffer times and supplements[12]. However, the running times and safety headway times are still treated as given timetable design input and the train speed profiles are not optimised. Essential graphical output for the evaluation of train schedules in form of e.g. standard time-distance, speed-distance and headway time distributions is missing in most mathematical programming publications, which is an important barrier for their application in practice.

2.3 Real-time rescheduling

Smaller train delays (one to two minutes) are recovered automatically due to existing running time supplements (at least 3 % on top of the minimum technical running time) and knock-on delays are avoided or reduced by buffer times (at least one minute) provided in the timetable. Larger delays of individual trains may disturb the train traffic, while technical failures lead mostly to disruptions of train operations at least in one direction lasting longer than one hour. Real-time rescheduling models can support dispatchers and traffic controllers in recognizing and solving route conflicts quickly. Regular train delays that lead to congestion of trains at junctions and stations and may propagate over (parts of) the network, so far, are handled locally by simple dispatching measures (holding, rerouting, reordering, cancellation) based on experience. Major disruptions due to technical failures, very bad weather or accidents are managed by (centralised) traffic controllers using (static) contingency plans. On densely occupied lines, in particular single track sections every disruption reduces the track capacity significantly so that cancelling some train services is unavoidable. The efficiency of the dispatching decisions may be sub-optimal, because they are fed only by radio communications, limited visual network traffic incident information and cannot predict well the impact of their measures on the local and regional network traffic.

During the past decade, a few computerised real-time rescheduling tools have been developed that can and must generate quickly (near) optimal timetables for disturbed/disrupted local and regional networks[13-20].

Real-time rescheduling models need to address and solve subsequently:

1)Data loading from and communications with the signalling, safety, traffic control and interlocking systems.

2)Route assignment to each train.

3) Detection and resolution of potential headway and route conflicts.

4)Determination of exact arrival and departure times at the borders of the network, intermediate stations, and relevant signals/junctions/crossings.

5)Adaptation of speed profiles.

None of these tools was connected, communicated and tested until today in real-time with data processors and traffic control operators of railway undertakings. All tools had to compile previously saved copies of log files containing the train schedules, signal box and interlocking messages as input data for testing. The output was then computed offline in laboratories, because the railway undertakings still hesitated to let test and demonstrate the use of rescheduling tools simultaneously in real world traffic control operations. That means the proposed dispatching measures in case of incidents and new real-time traffic plans could not be presented online to traffic controllers on duty in order to be confirmed or rejected and the performance of the rescheduling tool be compared with the dispatching decisions made by dispatchers.

Nonetheless, an innovative framework for closed-loop control of railway traffic during perturbations has been developed and demonstrated recently by means of simulation in case studies on four main railway corridors in United Kingdom, the Netherlands, Sweden and Norway[21]. Optimal Real-Time Traffic Plans based on traffic predictions over a given optimisation horizon have been computed and presented to a human dispatcher by means of a Human-Machine Interface. If accepted, the plans can be implemented directly by an Automatic Route Setting module through setting up the optimised train routes and transmitting speed advices for energy-efficient driving by the Driver Advisory System. Two different conflict detection and resolution modules (ROMA and RECIFE) have been adopted for the simulated Iron Ore line in Sweden/Norway in order to compare their performance.

The existing models for (optimised) rerouting and rescheduling in case of incidents and (partial) track blockage differ with regard to scope (often restricted to a few standard (passing) routes within interlocking areas), discretisation (macro-/meso-/microscopic infrastructure; train length and operation time steps (position, speed, acceleration, deceleration)), and discrete event or synchronous computation of track occupation/clearance, interlocking times with (out) partial route release, headway and corresponding blocking times. The applied mathematical integer programming methods for route and headway conflict detection range from e.g. Alternative (job-shop disjunctive graphs with train speed coordination[14-16], Bi-level Resource Tree Conflict Graph[17], Resource-based set-packing with speed alteration on entrance of block sections[18] to Mixed-integer linear program without speed variations (Pellegrini). In general, heuristic algorithms are needed to solve the rerouting and rescheduling problem within short time (one to two minutes) in order to satisfy the dispatcher's tasks. The preferred objectives of the real-time rescheduling models may be minimization of ① (maximum) consecutive train delays, ② consecutive passenger delays or ③ priority weighted timetable deviation. The minimization of total train delays is also used as objective. However, this objective is infected by primary delays, which occur independently from applying a rescheduling tool, whereas it can reduce the amount of knock-on delays more or less.

2.4 Driver advisory systems

Train drivers cannot precisely determine the earliest and latest time to start coasting and braking in order to maximize energy-saving and to arrive just on time, respectively. Only well trained and experienced train drivers know the amount of available running time supplement of their trains' trip and may recover (partly) from delays. Current train Driver Advisory Systems (DAS), if applied on top of Automatic Train Protection (ATP)/Automatic Train Control (ATC) systems, are bound to the simple communication of the amount of actual train delay (scaled in minutes) and predetermined local speed advices for regular train operation without considering the impact of actual train delays and traffic congestion in the network. Some Urban Rail Rapid Transit systems in Europe, North America and Japan have implemented on-board a kind of Automatic Cruise Control (ACC) that controls continuously the individual trains' acceleration, actual speed and deceleration according to the nominal speed profile, distance travelled, traction/braking force and safety headway required.

Intelligent driver advisory systems can make use of real-time traffic information generated by the signalling and safety systems, which are communicated via digital radio/Radio Block Centre (RBC) to the central traffic control unit. Flexible speed advices are required in particular for densely occupied railway lines operated by a mix of trains with different maximum speed levels and stop patterns, heavily loaded (freight) trains and at abnormal weather conditions. The central traffic control unit then computes and transmits globally optimised speed profiles in real-time to the on-board unit of each train involved in order to generate conflict-free and energy-optimal speed advices at local level. The DAS system architecture may be central, intermediate or on-board

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depending on where the re-computation of speed trajectories and speed advices, respectively, takes place[22]. The development of intelligent algorithms for the ①real-time prediction of train event times, ② computation and communication of accurate advisory speed changes based on optimal speed profiles ③at open track sections and in interlocking areas is a very challenging actual research topic[23-25]. Proven DAS systems can assure conflict-free train operations, reduce train delays, improve punctuality of train services and save energy. The advisory speed information is not-vital and would be overruled by the ATP/ATC system in case of over-speed, headway or route conflict.

3 Conclusions

The attractiveness, transport volume and market share of the railways increase, if the capacity of the infrastructure, quality of train services, accuracy and reliability of real-time process information was improved. This can be achieved by an integrated approach for lifting the treasure of existing Big Railway Data through sharing transport, technical, operations, safety and business data, developing advanced statistical analysis and learning methods in order to describe and predict better the determinants of real train speed, punctuality, capacity and energy consumption. Further research on the spatial and temporal distribution of railway transport, traffic and performance line by line, as well as local, regional and national networks, will stimulate the development, test and faster implementation of robust timetables, while the introduction of efficient decision support tools for real-time rescheduling of train schedules can minimise the impact of incidents and disruptions on capacity and quality of operations. The dedicated railway infrastructure and high performance of train control and safety systems favours automatic piloting of main line and even regional trains[26].

The most important actual barriers for faster and (near optimal) re-planning of railway operations in case of traffic disturbances and disruptions are not limited technical resources or computational power, but current human competences of timetable planners, train drivers and traffic controllers, as well as organisational barriers due to the separation between infrastructure management and train operating companies. The reticence of human actors against innovative train driving and rescheduling can be resolved by information, training and incentivising. The elimination of organisational barriers in the railway industry require wise political governess dominated by societal aims and not by fragmented business goals.

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