

北京交通大学

2023 年知行奖学金（研究生）

支撑材料

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2023 年 4 月 13 日

研究成果应用和转化

证 明

兹证明：

北京交通大学经济管理学院博士研究生陈炳尧，学号18113068，作为第二完成人撰写的国家自然科学基金重点项目指南建议《碳达峰、碳中和导向下的城市轨道交通企业“能源流-碳流-价值流”会计研究》，经学校科学技术研究院提报至国家自然科学基金委员会，被国家自然科学基金2022年重点项目指南采纳。

北京交通大学科学技术研究院



王冬梅

国家自然科学基金 2022 年重点项目指南建议

“碳达峰+碳中和”导向下的城市轨道交通企业
的“能源流-碳流-价值流”会计研究



提报日期：2021 年 4 月 24 日

提报单位：北京交通大学

提报人：郭雪萌 陈炳尧

1. 现实背景与问题提出

1.1 现实背景

2020 年 9 月 22 日，习近平总书记宣布，“我国二氧化碳排放力争于 2030 年前达到峰值，努力争取 2060 年前实现碳中和”。针对此目标，我国制定了碳排放控制的主要措施：

2030 年前：

(1) 受工业化和城镇化进程以及经济较快发展的影响，能源需求仍然在增长。应大力改善能源结构，使得新增长的能源需求主要由新增的非化石能源供应来满足，保证煤炭、石油等化石能源基本不再增加；(2) 通过替代、回收和分解等技术控制工业过程的二氧化碳排放；(3) 控制非二氧化碳温室气体的排放。

2030 年后：

交叉融合板块

管理科学部

2021年度管理科学部共接收重点项目申请143项，资助35项，直接费用平均资助强度约203万元/项。

管理科学部在“十四五”期间逐年发布重点项目立项领域。重点项目应针对能推动学科发展、有望做出创新性成果并产生一定国际影响的前沿科学问题；应切实围绕经济建设、社会发展、改革开放和提升我国综合竞争力所急需解决且有可能解决的一些重大管理理论与应用研究问题；应立足探索有中国特色的管理理论与规律的科学问题，在已有较好基础的研究方向或学科生长点开展深入、系统的创新性研究。

本《指南》中阐述的重点项目领域是对主要研究方向的概括，申请项目名称不一定要与下列重点项目领域名称完全一致。申请人及研究团队应在相关研究领域有较好的研究基础，充分发挥本人及团队的学术优势，明确研究目标，突出研究重点，能够抓准并切实解决其中的一个或若干个关键科学问题，在理论上有所创新。同时要充分重视理论联系实际，力求从我国国情出发，面向国家重大需求，凝练出重要的管理科学问题，展开深入研究，以提供指导解决实际管理问题的新途径；强调以科学方法论为指导，注重科学方法的使用，强调以实际数据/案例作为研究的信息基础。

2022年度管理科学部重点项目资助领域

申请管理科学部重点项目，申请代码1应当选择科学部重点项目资助领域名称后标明的申请代码，“附注”不予受理。

2022年度国家自然科学基金项目指南（上册）

2022年度本科学部提出
接费用资助强度约为210万。

1. 智能制造管理理论与方法
- (1) 基于数字孪生的智能制造
- (2) 智造服务平台模式创新
- (3) 面向智能制造的定制生产
- (4) 低碳智能制造的全生命周期管理
- (5) 重大技术装备的生产管理
2. 民航一体化运营优化和保障
3. 在线交易平台中的行为与决策
4. 在线直播新零售模式与供应链管理
5. 基于区块链的物联网安全管理
6. 大型交通枢纽及周边交通组织
7. 人机系统的行为与管理

8. 数智时代的企业经营与管理研究

- (1) 数智时代的企业营销创新理论研究（G0207）
- (2) 数智时代的组织模式变革与员工行为（G0208）
- (3) 数智时代的数据应用与组织效能研究（G0209）
- (4) 数智时代的企业投融资与风险管理（G0210）
- (5) 数智时代的运营管理与商业模式创新（G0211）

9. 企业战略与创业的微观基础理论研究（G0201）

10. 中国企业创新链产业链融合发展模式（G0202）

11. 企业开展基础研究的动力机制与模式（G0203）

12. 平台企业的领导力模式和理论研究（G0204）

13. 基于企业“价值流-能源流-碳流”的会计研究（G0206）

14. 数字经济发展基础理论

- (1) 数字经济测度理论与方法研究（G0301）
- (2) 数字经济变革下金融风险治理理论研究（G0303、G0307）
- (3) 数字经济变革对就业的影响机制与政策研究（G0305、G0313）

15. 区域经济与产业经济发展基础理论

(1) 老工业基地振兴发展的新动能培育理论模式与关键要素体系（G0309、G0312）

- (2) 市场主体活力激发与营商环境优化（G0309、G0310、G0312）
- (3) 乡村振兴战略下城乡融合发展模式与产业创新（G0309、G0311）
- (4) “双碳”目标约束下的经济产业影响与可持续发展理论（G0309、G0314）

16. 环境与生态管理领域

- (1) 基于复杂系统的碳中和关键减排技术风险管理（G0411）
- (2) 人工智能技术驱动的环境风险复杂系统动态模拟与治理（G0411）
- (3) 基于复杂系统建模的碳中和多维政策模拟仿真研究（G0411）
- (4) 能源转型的复杂机理及其经济社会环境影响（G0411、G0412）

17. 公共管理与社会治理领域

- (1) 公共治理体系变革创新的理论与机制（G0401）
- (2) 大数据驱动下的社区治理理论、范式与政策（G0401）
- (3) 社会治理中的社会智能体系构建与社会计算（G0410）
- (4) 数智赋能的信息资源与知识管理理论变革（G0414）

北京市四网融合存在问题及融合路径建议



提报日期：2022 年 10 月 20 日

提报单位：北京交通大学

提报人：郭雪萌 经济管理学院 教授

孔令鹏 经济管理学院 博士生

陈炳尧 经济管理学院 博士生

一、北京市四网融合中存在的问题

1. 不同层次轨道交通发展不均衡，网络级配不合理，市郊铁路弱势明显

未来北京市的发展将呈现“一核两翼”的空间格局，尽管已经开通了市郊铁路城市副中心线，但另一翼雄安新区的通勤类轨道交通尚未完全打通（已有城际，高铁在建），并且其余郊区新城也多以地铁为主。地铁存在地铁站间距短、旅行速度慢和换乘次数多等缺陷，并不适用于过长的通勤距离。因此现阶段北京市四网发展不均衡，地铁线路较多且分担了较多的客流，《北京城市总体规划（2016 年—2035 年）》也对城际铁路由明显的近、远期建设目标，而市郊铁路等线路较少市郊铁路供给明显不足，其需求、服务目标、新建还是利旧、投资体制等都尚未明确。

北京市发展和改革委员会办公室

成果应用证明

北京交通大学北京综合交通发展研究院郭雪萌教授于2022年9月撰写的《北京市四网融合存在问题及融合路径建议》研究报告，该成果在推动北京市“四网融合”建设方面提出的以“‘枢纽先行，站点分级，便利优先’原则推动站城融合”“运服联合，制度配合，向轨道交通服务一体化转变”等建议被我委决策采用，纳入到我委组织编制的《促进平原新城高质量发展提升平原新城综合承载能力2023年工作要点》政策文件中，该文件拟于2023年一季度发布，在“加强对外快速交通联系”“加快推进‘站城融合’发展”等内容中均有具体体现，发挥了积极的支撑作用。

特此证明。

北京市发展和改革委员会办公室

2023年2月13日



作为主要贡献者完成国家自然科学基金面上项目《城市轨道交通PPP模式“客流-价值流”绩效评价体系研究》、专项项目《科学基金预算增长机制与预算绩效管理优化研究》。研究成果获得国家自然科学基金委、科技部科技评估中心认可，转化为多篇高水平学术论文。

科学基金中长期及“十四五”基础研究经费投入 预算测算结果及说明

(国家评估中心、北京交通大学课题组)

根据我国创新发展战略要求，结合国家自然科学基金在基础研究未来发展愿景，通过对美国、日本、德国、法国等创新型国家的比较借鉴，初步形成了三种科学基金基础研究经费投入预算测算方案，对各测算方案采用指标和依据进行说明如下。

一、根据世界创新型国家发展的主要特征进行测算

(一) 测算依据

这一方案的测算依据及预设标准包括国民生产总值（GDP）增速预期、“十四五”末期 R&D 经费投入强度（R&D/GDP）目标值及增幅预期等因素，具体测算依据和方法如下。

DOI:10.13546/j.cnki.tjyj.2022.12.029

财经纵横

全要素生产率的测度与国际比较

郭雪萌¹, 陈炳尧¹, 王 琨², 李金磊²

(1.北京交通大学 经济管理学院,北京 100044;2.国家自然科学基金委员会 财务局,北京 100085)

摘 要:文章运用随机前沿模型测度我国及主要创新型国家2001—2018年的全要素生产率,并探究全要素生产率的影响因素,揭示关键要素对我国全要素生产率的影响规律。研究发现:我国全要素生产率与创新型国家相比仍有进步空间,但逐年提高的改善趋势已经显现,与创新型国家平均水平的相对差距稳步缩小。我国要素投入呈现资源利用率提高的趋势特征,体现出投入产出动态平衡的良性发展态势。不同要素对我国全要素生产率的影响效应与规律存在差异性、层级性,第三产业的主导作用越来越强,科技经费与人力投入发挥了稳定持续的提升作用。

关键词:全要素生产率;高质量发展;随机前沿分析

中图分类号:F124 **文献标识码:**A **文章编号:**1002-6487(2022)12-0146-04

0 引言

党的十九大报告首次提出“提高全要素生产率”。“十四五”规划明确构建中国经济发展新格局,以提高全要素生产率,推动经济高质量发展。全要素生产率作为判断经济增长质量和发展潜力的一项重要标准,体现了“集约式增长”的发展理念,契合了我国以创新驱动高质量发展的深刻内涵。准确把握全要素生产率的内涵实质,科学测度全要素生产率并厘清其影响因素,是探索全要素生产率提升路径的重要前提。“生产率”一词最早提出于1766年,《英国大百科全书》将其定义为“生产所得与生产这些所得

涵盖国家层面^[1-4]、区域层面^[5-9]、产业层面^[10],以及各类测度方法的辨析与优化^[10,11]。

目前,全要素生产率多以单一主体为测度对象,缺乏基于比较视野的定量研究,难以反映不同主体间的效率差异从而制定科学的目标依据。另外,已有研究对全要素生产率的内涵尚未达成共识,使用的测度方法也不尽相同,导致结果差异较大、可比性较弱。因此,本文以国际比较为切入点,采用随机前沿模型测度世界18个创新型国家与我国2001—2018年的全要素生产率,基于可比性原则分析国家间的相对效率差异,进而从“形”和“势”两个维度研究不同要素对于全要素生产率的影响效应与规律,旨在为科学评价我国全要素生产率、厘清提高全要素生产率的



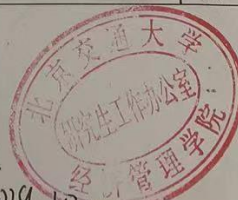
- 2022年9月，代表学校赴太原全程主持太原市城市轨道交通第二期建设规划项目磋商、研究、投标等事宜，已取得阶段性成果。

响 应 文 件 项目名称：<u>太原市城市轨道交通第二期建设规划（2023-2028年）项目投融资及建设模式研究专题编制</u> 项目编号：<u>1401992022CCS00950</u> 投标包（项）数：<u>1 包</u> 供应商全称：<u>北京交通大学</u> 法定代表人或授权代表：<u>郭雪莉</u> 日期：2022年10月16日	响 应 文 件 项目名称：<u>太原市城市轨道交通第二期建设规划（2023-2028年）项目投融资及建设模式研究专题编制</u> 项目编号：<u>1401992022CCS00950</u> 投标包（项）数：<u>1 包</u> 供应商全称：<u>北京交通大学</u> 法定代表人或授权代表：<u>郭雪莉</u> 日期：2022年10月16日	响 应 文 件 (资格审查部分) 项目名称：<u>太原市城市轨道交通第二期建设规划（2023-2028年）项目投融资及建设模式研究专题编制</u> 项目编号：<u>1401992022CCS00950</u> 投标包（项）数：<u>1 包</u> 供应商全称：<u>北京交通大学</u> 法定代表人或授权代表：<u>郭雪莉</u> 日期：2022年10月16日
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经济管理学院 2022 年秋季学期研究生外出三方协议及承诺书

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紧急联系人 (直系亲属)	陈宝诚	紧急联系人 联系方式	13606388926		
请假离校事由 (详细写明)	代表学校前往太原市政府参与校企合作项目磋商和现场交流				
离校类别	1、京内一天以内 2、京内两周以内 3、京内两周以上 4、京外				
在校中申请 外出情况	1、出校地点: 山西省太原市杏花岭区府西街 246 号轨道交通建设服务中心 (连续十天以上无新增病例) 山西大同台东里 50-73 2、出行方式: G601 (北京丰台—太原南); G612 (太原南—北京丰台) 3、请假时间段: 2022 年 9 月 13 日—2022 年 9 月 15 日 2022 年 10 月 31 日				
本人郑重承诺: 1、上述全部信息真实有效,返校系统上报信息准确,无瞒报、谎报现象。 2、请假期间,严格按照请假时间出校和返校。 3、按照学校防疫要求,按时完成“每日填报”及“早、午、晚检”健康打卡,有事及时向导师及学院报备。出校期间,严格做好个人防护,保持个人卫生、不聚集。 4、本人承诺从学校到工作室或者实习单位“两点一线”,不参与任何聚集、聚餐(校外就餐)、聚会。 5、在校外实习或者科研期满后主动向学院、导师、辅导员汇报。 6、及时浏览学院主页查看相关信息,严格遵守校园防疫和管理规定,不影响校内防疫管理及各个培养环节。 7、离校期间的个人安全由本人负责,并遵守所在地的防疫政策。 8、如违反以上情况,本人愿意承担相关责任。特此承诺。 本人承诺,所到及途经区域承诺人/申请人签字: 陈炳尧 7 日内无新增,返校后本人严格遵守当地及学 校防疫规定,自行隔离七天五检后再返校(五天两检)。					
导师意见	同意 导师签字: 郭雪萌 2022 年 9 月 10 日				
学院意见	负责人签字: 郭江 盖章: 2022 年 9 月 11 日				

经核实,该生所在区域近 7 日无新增
学生,明确回京后严格执行隔离再入校





项目批准号	72272010
申请代码	A0206
项目申请部门	社会科学部(1)
依托单位代码	10004400500017-0002



7227201010002839

国家自然科学基金
资助项目计划书
(预算制项目)

资助类别：面上项目

类别说明：

附注说明：

项目名称：基于“客流-能源流-碳流”的城市轨道交通低碳扩展效应研究

直接费用：45万元 执行年限：2023.01-2026.12

负责人：郭雪萌

通讯地址：北京市海淀区上园村3号北京交通大学经济管理学院

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依托单位：北京交通大学

联系人：张耀月 电 话：010-51688033

填表日期：2022年09月21日

国家自然科学基金委员会制

Version: 1.002.839

国家自然科学基金资助项目批准通知

(预算制项目)

郭雪萌 先生/女士：

根据《国家自然科学基金条例》、相关项目管理办法规定和专家评审意见，国家自然科学基金委员会（以下简称自然科学基金委）决定资助您申请的项目。项目批准号：72272010，项目名称：基于“客流-能源流-碳流”的城市轨道交通低碳扩展效应研究，直接费用：45万元，项目起止年月：2023年01月至 2026年 12月，有关项目的评审意见及修改意见附后。

关于国家自然科学基金资助项目批准及有关事项的通知

郭雪萌 先生/女士：

根据《国家自然科学基金条例》的规定和专家评审意见，国家自然科学基金委员会（以下简称自然科学基金委）决定批准资助您的申请项目。项目批准号：J2124009，项目名称：联合基金财务管理体系建设与优化研究，直接费用：45万元，项目起止年月：2021年07月至 2022年 12月，有关项目的评审意见及修改意见附后。

- 国自科“面上”《基于“客流-能源流-碳流”的城市轨道交通低碳扩展效应研究》
- 国自科“专项”《联合基金财务管理体系建设与优化研究》

论文发表情况

后附：

1. 英文期刊论文检索报告
2. SSCI 收录期刊及影响因子（交大科技处 2022-1-12 最新发布）
3. 英文期刊论文录用通知、出版通知及论文原文
4. 中文期刊论文原件及复印件

编号: CS2022-DF-949

检索报告



检索委托人: 陈炳尧

委托人单位: 北京交通大学经济管理学院

检索时间段: 2020—2022 年

检索内容与结果:

检索数据库		检索结果
SSCI/SCI-EXPANDED	(收录)	3 篇

(详细内容见附件)

北京交通大学图书馆

2022 年 10 月 7 日

检索专用章



附件：SSCI/SCI-EXPANDED 收录情况

第 1 条，共 3 条

标题: Public-Private Partnership Infrastructure Investment and Sustainable Economic Development: An Empirical Study Based on Efficiency Evaluation and Spatial Spillover in China

作者: Chen, BY (Chen, Bingyao)

来源出版物: SUSTAINABILITY 卷: 13 期: 15 文献号: 8146 DOI: 10.3390/su13158146 出版年: AUG 2021

Web of Science 核心合集中的 "被引频次": 6

被引频次合计: 6

入藏号: WOS:000682314600001

语言: English

文献类型: Article

地址: [Chen, Bingyao] Beijing Jiaotong Univ, Sch Econ & Management, Beijing 100044, Peoples R China.

通讯作者地址: Chen, BY (通讯作者), Beijing Jiaotong Univ, Sch Econ & Management, Beijing 100044, Peoples R China.

电子邮件地址: 18113068@bjtu.edu.cn

Affiliations: Beijing Jiaotong University

IDS 号: TW3OT

eISSN: 2071-1050

输出日期: 2022-10-07

第 2 条，共 3 条

标题: Public-Private Partnership and Transport Infrastructure Investment Efficiency: Evidence from Countries along the 21st-Century Maritime Silk Road

作者: Chen, BY (Chen, Bingyao); Guo, XM (Guo, Xuemeng)

来源出版物: JOURNAL OF COASTAL RESEARCH 特刊: 112 页: 269-274 DOI: 10.2112/JCR-SI112-073.1 出版年: FAL 2020

Web of Science 核心合集中的 "被引频次": 2

被引频次合计: 2

入藏号: WOS:000589340200073

语言: English

文献类型: Article

地址: [Chen, Bingyao; Guo, Xuemeng] Beijing Jiaotong Univ, Sch Econ & Management, Beijing 100044, Peoples R China.

通讯作者地址: Guo, XM (通讯作者), Beijing Jiaotong Univ, Sch Econ & Management, Beijing 100044, Peoples R China.

电子邮件地址: xmguo@bjtu.edu.cn

Affiliations: Beijing Jiaotong University

IDS 号: OR2YF

ISSN: 0749-0208

eISSN: 1551-5036

输出日期: 2022-10-07

第 3 条，共 3 条

标题: Public-Private Partnership Transportation Investment and Low-Carbon Economic Development: An Empirical Study Based on Spatial Spillover and Project Characteristics in China

作者: Guo, XM (Guo, Xuemeng); Chen, BY (Chen, Bingyao); Feng, YT (Feng, Yuting)

来源出版物: SUSTAINABILITY 卷: 14 期: 15 文献号: 9574 DOI: 10.3390/su14159574 出版年: AUG 2022

Web of Science 核心合集中的 "被引频次": 0

被引频次合计: 0

入藏号: WOS:000839359800001

语言: English

文献类型: Article

地址: [Guo, Xueming; Chen, Bingyao; Feng, Yuting] Beijing Jiaotong Univ, Sch Econ & Management, Beijing 100044, Peoples R China.

通讯作者地址: Chen, BY (通讯作者), Beijing Jiaotong Univ, Sch Econ & Management, Beijing 100044, Peoples R China.

电子邮件地址: 18113068@bjtu.edu.cn

Affiliations: Beijing Jiaotong University

IDS 号: 3S1JV

eISSN: 2071-1050

输出日期: 2022-10-07



SSCI收录期刊及影响因子（中国科学技术信息研究所公布）

来源：交大科技处官网（<https://kyy.bjtu.edu.cn/cms>） 期刊源检索-最新SSCI收录期刊及影响因子（2022-01-12发布）

SSCI-JCR数据

当前位置：期刊源检索 - SSCI-JCR数据

2020年SSCI收录期刊及影响因子（中国科学技术信息研究所公布）

2022-01-12

分类	期刊全称	总被引频次	影响因子	ISSN	期刊数量	排序	分区
ENVIRONMENTAL STUDIES	Nature Climate Change	36,321	25.29	1758-678X	125	1	一区
ENVIRONMENTAL STUDIES	Nature Sustainability	4,664	19.346	2398-9629	125	2	一区
ENVIRONMENTAL STUDIES	Annual Review of Environment and Resources	5,711	11.108	1543-5938	125	3	一区
ENVIRONMENTAL STUDIES	TOURISM MANAGEMENT	37,117	10.967	0261-5177	125	4	一区
ENVIRONMENTAL STUDIES	Business Strategy and the Environment	10,505	10.302	0964-4733	125	5	一区
ENVIRONMENTAL STUDIES	Environmental Innovation and Societal Transitions	3,530	9.68	2210-4224	125	6	一区
ENVIRONMENTAL STUDIES	GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	23,032	9.523	0959-3780	125	7	二区
ENVIRONMENTAL STUDIES	Corporate Social Responsibility and Environmental Management	6,643	8.741	1535-3958	125	8	二区
ENVIRONMENTAL STUDIES	Wiley Interdisciplinary Reviews-Climate Change	5,062	7.385	1757-7780	125	9	二区
ENVIRONMENTAL STUDIES	Energy Research & Social Science	9,250	6.834	2214-6296	125	10	二区
ENVIRONMENTAL STUDIES	ENVIRONMENTAL POLITICS	3,989	6.71	0964-4016	125	11	二区
ENVIRONMENTAL STUDIES	ENVIRONMENT AND PLANNING D-SOCIETY & SPACE	6,131	6.664	0263-7758	125	12	二区
ENVIRONMENTAL STUDIES	ENVIRONMENT AND BEHAVIOR	8,885	6.222	0013-9165	125	13	二区
ENVIRONMENTAL STUDIES	ENERGY POLICY	60,369	6.142	0301-4215	125	14	二区
ENVIRONMENTAL STUDIES	LANDSCAPE AND URBAN PLANNING	22,745	6.142	0169-2046	125	15	二区
ENVIRONMENTAL STUDIES	ORGANIZATION & ENVIRONMENT	2,766	6.116	1086-0266	125	16	二区
ENVIRONMENTAL STUDIES	Review of Environmental Economics and Policy	1,731	6.049	1750-6816	125	17	二区
ENVIRONMENTAL STUDIES	PROGRESS IN PLANNING	1,283	5.688	0305-9006	125	18	二区
ENVIRONMENTAL STUDIES	Climate Services	664	5.656	2405-8807	125	19	二区
ENVIRONMENTAL STUDIES	RESOURCES POLICY	7,000	5.634	0301-4207	125	20	二区
ENVIRONMENTAL STUDIES	TRANSPORTATION RESEARCH PART D-TRANSPORT AND ENVIRONMENT	12,035	5.495	1361-9209	125	21	二区
ENVIRONMENTAL STUDIES	Ecosystem Services	7,490	5.454	2212-0416	125	22	二区
ENVIRONMENTAL STUDIES	LAND USE POLICY	22,020	5.398	0264-8377	125	23	二区
ENVIRONMENTAL STUDIES	ECOLOGICAL ECONOMICS	32,197	5.389	0921-8009	125	24	二区
ENVIRONMENTAL STUDIES	HABITAT INTERNATIONAL	8,872	5.369	0197-3975	125	25	二区
ENVIRONMENTAL STUDIES	COMPUTERS ENVIRONMENT AND URBAN SYSTEMS	5,075	5.324	0198-9715	125	26	三区
ENVIRONMENTAL STUDIES	JOURNAL OF ENVIRONMENTAL PSYCHOLOGY	15,100	5.192	0272-4944	125	27	三区

ENVIRONMENTAL STUDIES	Annual Review of Resource Economics	1,160	5.184	1941-1340	125	28	三區
ENVIRONMENTAL STUDIES	CLIMATE POLICY	3,582	5.085	1469-3062	125	29	三區
ENVIRONMENTAL STUDIES	Sustainable Production and Consumption	1,403	5.032	2352-5509	125	30	三區
ENVIRONMENTAL STUDIES	REGIONAL STUDIES	11,137	4.672	0034-3404	125	31	三區
ENVIRONMENTAL STUDIES	URBAN STUDIES	17,626	4.663	0042-0980	125	32	三區
ENVIRONMENTAL STUDIES	JOURNAL OF ENVIRONMENTAL ECONOMICS AND MANAGEMENT	8,559	4.624	0095-0696	125	33	三區
ENVIRONMENTAL STUDIES	ENVIRONMENTAL IMPACT ASSESSMENT REVIEW	5,305	4.549	0195-9255	125	34	三區
ENVIRONMENTAL STUDIES	URBAN FORESTRY & URBAN GREENING	8,321	4.539	1618-8667	125	35	三區
ENVIRONMENTAL STUDIES	EUROPEAN URBAN AND REGIONAL STUDIES	1,942	4.49	0969-7764	125	36	三區
ENVIRONMENTAL STUDIES	ECOLOGY AND SOCIETY	13,955	4.403	1708-3087	125	37	三區
ENVIRONMENTAL STUDIES	Climate and Development	1,890	4.28	1756-5529	125	38	三區
ENVIRONMENTAL STUDIES	Anthropocene Review	772	4.182	2053-0196	125	39	三區
ENVIRONMENTAL STUDIES	MARINE POLICY	12,969	4.173	0308-597X	125	40	三區
ENVIRONMENTAL STUDIES	ENVIRONMENT	1,487	4.103	0013-9157	125	41	三區
ENVIRONMENTAL STUDIES	Climate Risk Management	1,248	4.09	2212-0963	125	42	三區
ENVIRONMENTAL STUDIES	Environment and Planning A-Economy and Space	13,953	4.056	0308-518X	125	43	三區
ENVIRONMENTAL STUDIES	Global Environmental Politics	2,005	4.055	1526-3800	125	44	三區
ENVIRONMENTAL STUDIES	International Journal of Sustainable Transportation	2,123	3.929	1556-8318	125	45	三區
ENVIRONMENTAL STUDIES	Housing Theory & Society	1,313	3.744	1403-6096	125	46	三區
ENVIRONMENTAL STUDIES	Regional Environmental Change	6,469	3.678	1436-3798	125	47	三區
ENVIRONMENTAL STUDIES	FOREST POLICY AND ECONOMICS	5,784	3.673	1389-9341	125	48	三區
ENVIRONMENTAL STUDIES	Environment and Planning B-Urban Analytics and City Science	5,282	3.619	2399-8083	125	49	三區
ENVIRONMENTAL STUDIES	International Journal of Housing Policy	960	3.612	1949-1247	125	50	三區
ENVIRONMENTAL STUDIES	Extractive Industries and Society-An International Journal	2,209	3.586	2214-790X	125	51	三區
ENVIRONMENTAL STUDIES	POPULATION AND ENVIRONMENT	1,765	3.537	0199-0039	125	52	三區
ENVIRONMENTAL STUDIES	HOUSING STUDIES	3,865	3.516	0267-3037	125	53	三區
ENVIRONMENTAL STUDIES	Environmental Education Research	4,533	3.512	1350-4622	125	54	三區
ENVIRONMENTAL STUDIES	Journal of the Association of Environmental and Resource Economists	956	3.478	2333-5955	125	55	三區
ENVIRONMENTAL STUDIES	Land	2,389	3.398	2073-445X	125	56	三區
ENVIRONMENTAL STUDIES	Sustainability Accounting Management and Policy Journal	1,079	3.354	2040-8021	125	57	三區
ENVIRONMENTAL STUDIES	EUROPEAN PLANNING STUDIES	5,792	3.269	0965-4313	125	58	三區
ENVIRONMENTAL STUDIES	Sustainability	71,638	3.251	2071-1050	125	59	三區
ENVIRONMENTAL STUDIES	Conservation & Society	1,386	3.203	0972-4923	125	60	三區

ENVIRONMENTAL STUDIES	ENVIRONMENT AND URBANIZATION	3,125	3.2	0956-2478	125	61	三区
ENVIRONMENTAL STUDIES	Carbon Management	1,278	3.182	1758-3004	125	62	三区
ENVIRONMENTAL STUDIES	Natural Hazards Review	2,006	3.169	1527-6988	125	63	三区
ENVIRONMENTAL STUDIES	Environment and Planning C-Politics and Space	3,526	3.103	2399-6544	125	64	四区
ENVIRONMENTAL STUDIES	Energy & Environment	1,060	2.945	0958-305X	125	65	四区
ENVIRONMENTAL STUDIES	Transnational Environmental Law	375	2.923	2047-1025	125	66	四区
ENVIRONMENTAL STUDIES	JOURNAL OF ENVIRONMENTAL EDUCATION	2,371	2.915	0095-8964	125	67	四区
ENVIRONMENTAL STUDIES	PAPERS IN REGIONAL SCIENCE	3,197	2.858	1056-8190	125	68	四区
ENVIRONMENTAL STUDIES	Environmental Policy and Governance	1,278	2.853	1756-932X	125	69	四区
ENVIRONMENTAL STUDIES	Environmental Communication-A Journal of Nature and Culture	1,501	2.848	1752-4032	125	70	四区
ENVIRONMENTAL STUDIES	SOCIETY & NATURAL RESOURCES	4,843	2.821	0894-1920	125	71	四区
ENVIRONMENTAL STUDIES	Utilities Policy	2,043	2.812	0957-1787	125	72	四区
ENVIRONMENTAL STUDIES	Weather Climate and Society	1,373	2.746	1948-8327	125	73	四区
ENVIRONMENTAL STUDIES	Science and Public Policy	2,719	2.725	0302-3427	125	74	四区
ENVIRONMENTAL STUDIES	JOURNAL OF REGIONAL SCIENCE	3,299	2.713	0022-4146	125	75	四区
ENVIRONMENTAL STUDIES	RESOURCE AND ENERGY ECONOMICS	2,592	2.688	0928-7655	125	76	四区
ENVIRONMENTAL STUDIES	International Environmental Agreements-Politics Law and Economics	1,131	2.649	1567-9764	125	77	四区
ENVIRONMENTAL STUDIES	ANNALS OF REGIONAL SCIENCE	2,593	2.646	0570-1864	125	78	四区
ENVIRONMENTAL STUDIES	International Journal of Climate Change Strategies and Management	690	2.645	1756-8692	125	79	四区
ENVIRONMENTAL STUDIES	DISASTERS	3,403	2.641	0361-3666	125	80	四区
ENVIRONMENTAL STUDIES	REGIONAL SCIENCE AND URBAN ECONOMICS	4,552	2.613	0166-0462	125	81	四区
ENVIRONMENTAL STUDIES	Energy Efficiency	1,998	2.574	1570-646X	125	82	四区
ENVIRONMENTAL STUDIES	Review of European Comparative & International Environmental Law	643	2.541	2050-0386	125	83	四区
ENVIRONMENTAL STUDIES	Impact Assessment and Project Appraisal	1,462	2.524	1461-5517	125	84	四区
ENVIRONMENTAL STUDIES	ENVIRONMENTAL VALUES	1,038	2.518	0963-2719	125	85	四区
ENVIRONMENTAL STUDIES	GAIA-Ecological Perspectives for Science and Society	1,036	2.506	0940-5550	125	86	四区
ENVIRONMENTAL STUDIES	Local Environment	2,976	2.496	1354-9839	125	87	四区
ENVIRONMENTAL STUDIES	INTERNATIONAL REGIONAL SCIENCE REVIEW	1,426	2.477	0160-0176	125	88	四区
ENVIRONMENTAL STUDIES	Urban Policy and Research	930	2.448	0811-1146	125	89	四区
ENVIRONMENTAL STUDIES	CULTURAL GEOGRAPHIES	1,800	2.431	1474-4740	125	90	四区
ENVIRONMENTAL STUDIES	ENERGY JOURNAL	3,398	2.414	0195-6574	125	91	四区
ENVIRONMENTAL STUDIES	Journal of Housing and the Built Environment	1,516	2.414	1566-4910	125	92	四区
ENVIRONMENTAL STUDIES	Water Resources and Economics	345	2.371	2212-4284	125	93	四区

ENVIRONMENTAL STUDIES	International Journal of the Commons	1,110	2.253	1875-0281	125	94	四区
ENVIRONMENTAL STUDIES	INTERNATIONAL JOURNAL OF URBAN SCIENCES	596	2.242	1226-5934	125	95	四区
ENVIRONMENTAL STUDIES	ENVIRONMENTAL & RESOURCE ECONOMICS	6,034	2.181	0924-6460	125	96	四区
ENVIRONMENTAL STUDIES	Marine Resource Economics	1,131	2.147	0738-1360	125	97	四区
ENVIRONMENTAL STUDIES	Journal of Environment & Development	937	2.097	1070-4965	125	98	四区
ENVIRONMENTAL STUDIES	HARVARD ENVIRONMENTAL LAW REVIEW	367	2.091	0147-8257	125	99	四区
ENVIRONMENTAL STUDIES	LAND ECONOMICS	3,812	2.087	0023-7639	125	100	四区
ENVIRONMENTAL STUDIES	Water Alternatives-An Interdisciplinary Journal on Water Politics and Development	1,360	2.085	1965-0175	125	101	四区
ENVIRONMENTAL STUDIES	Journal of Agricultural Education & Extension	736	2.06	1389-224X	125	102	四区
ENVIRONMENTAL STUDIES	Landscape Research	1,879	2.055	0142-6397	125	103	四区
ENVIRONMENTAL STUDIES	JOURNAL OF ENVIRONMENTAL LAW	585	2	0952-8873	125	104	四区
ENVIRONMENTAL STUDIES	HUMAN ECOLOGY	3,490	1.993	0300-7839	125	105	四区
ENVIRONMENTAL STUDIES	Geografisk Tidsskrift-Danish Journal of Geography	394	1.963	0016-7223	125	106	四区
ENVIRONMENTAL STUDIES	ENVIRONMENT AND DEVELOPMENT ECONOMICS	1,960	1.939	1355-770X	125	107	四区
ENVIRONMENTAL STUDIES	COASTAL MANAGEMENT	1,302	1.922	0892-0753	125	108	四区
ENVIRONMENTAL STUDIES	Applied Spatial Analysis and Policy	561	1.9	1874-463X	125	109	四区
ENVIRONMENTAL STUDIES	Australasian Journal of Environmental Management	468	1.833	1448-6563	125	110	四区
ENVIRONMENTAL STUDIES	Environmental Hazards-Human and Policy Dimensions	1,203	1.827	1747-7891	125	111	四区
ENVIRONMENTAL STUDIES	NATURAL RESOURCES FORUM	1,247	1.821	0165-0203	125	112	四区
ENVIRONMENTAL STUDIES	Economics of Energy & Environmental Policy	398	1.657	2160-5882	125	113	四区
ENVIRONMENTAL STUDIES	Disaster Prevention and Management	1,750	1.521	0965-3562	125	114	四区
ENVIRONMENTAL STUDIES	Climate Change Economics	426	1.465	2010-0078	125	115	四区
ENVIRONMENTAL STUDIES	Water Economics and Policy	212	1.133	2382-624X	125	116	四区
ENVIRONMENTAL STUDIES	Nature + Culture	465	1.029	1558-6073	125	117	四区
ENVIRONMENTAL STUDIES	NATURAL RESOURCES JOURNAL	481	1	0028-0739	125	118	四区
ENVIRONMENTAL STUDIES	ECOLOGY LAW QUARTERLY	341	0.924	0046-1121	125	119	四区
ENVIRONMENTAL STUDIES	Problemy Ekorozwoju	220	0.859	1895-6912	125	120	四区
ENVIRONMENTAL STUDIES	ENVIRONMENTAL HISTORY	566	0.746	1084-5453	125	121	四区
ENVIRONMENTAL STUDIES	ENVIRONMENT AND HISTORY	349	0.714	0967-3407	125	122	四区
ENVIRONMENTAL STUDIES	Human Ecology Review	796	0.581	1074-4827	125	123	四区
ENVIRONMENTAL STUDIES	ENVIRONMENTAL ETHICS	541	0.283	0163-4275	125	124	四区
ENVIRONMENTAL STUDIES	Open House International	259	0.283	0168-2601	125	125	四区



CERTIFICATE OF ACCEPTANCE

Certificate of acceptance for the manuscript (**sustainability-1813750**) titled:
Public-Private Partnership Transportation Investment and Low-Carbon Economic
Development: An Empirical Study Based on Spatial Spillover and Project Characteristics
in China

Authored by:
Xuemeng Guo; Bingyao Chen; Yuting Feng

has been accepted in *Sustainability* (ISSN 2071-1050) on 01 August 2022



CERTIFICATE OF PUBLICATION

Certificate of publication for the article titled:

Public-Private Partnership Transportation Investment and Low-Carbon Economic Development: An Empirical Study Based on Spatial Spillover and Project Characteristics in China

Authored by:

Xuemeng Guo; Bingyao Chen; Yuting Feng

Published in:

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Article

Public-Private Partnership Transportation Investment and Low-Carbon Economic Development: An Empirical Study Based on Spatial Spillover and Project Characteristics in China

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Abstract: As the most widely used investment mode of transportation infrastructure in China, PPP has been regarded as an effective institutional tool by the Chinese government for the construction of efficient and sustainable transportation infrastructure, promoting high-quality economic development. In order to evaluate the economic sustainability of PPP, this paper innovatively takes the low-carbon economy as the research perspective and uses 276 cities of China from 2006 to 2018 as samples to comprehensively investigate the impact of transportation PPP investment on the low-carbon economy from the diversified dimensions of the overall effect, spatial effect, mediating effect, heterogeneous effect, lagged effect, and PPP project-level characteristics. The results show that: (1) transportation PPP investment markedly promotes low-carbon economic development in China, which is manifested as the dual improvement effects of benefits and efficiency; (2) transportation PPP investment has a positive spatial spillover effect that can promote the low-carbon economic development of neighboring cities; (3) transportation PPP investment can promote low-carbon economic development by promoting the upgrading of industrial structures, and furthermore has a spatial transmission mechanism; (4) impacts of transportation PPP investment in different subsectors are significantly heterogeneous; (5) transportation PPP investment has a continuous and stable impact on promoting the low-carbon economy in China; (6) the participation of state-owned enterprises and listed companies in PPP projects has a significant positive impact, and state-owned capital is more effective in projects with relatively large scale. All these provide reliable evidence for the far-reaching significance and practical value of transportation PPP investment on sustainable low-carbon economic development.

Keywords: PPP; transportation infrastructure investment; low-carbon economy; sustainable development; spatial spillover; projects characteristics



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1. Introduction

In the new age, the low-carbon economy has become an important development trend worldwide, which reveals the fundamental transformation of the human survival concept and economic development mode. As a major carbon emitter, China puts forward the environmental targets of carbon peaking and carbon neutrality, and the sustainability strategy of high-quality economic development. Transportation is a pioneer in the economic development of China, which has an priority mission of sustainable development. In the face of the increasing demand of transportation infrastructure construction, the supply mode which takes the government as the single body of investment and operation gradually exposes the drawbacks of the low supply efficiency and huge financial burden. At this point, a Public-Private Partnership (PPP) mode is highly promoted by the Chinese government due to its efficiency advantages. According to China's Ministry of Finance, by June 2022, China's total PPP investment in transportation had reached 5.8 trillion yuan, making China the world's largest transportation PPP market. The 14th Five-Year Plan of China emphasizes

giving full play to the role of PPP to sustain the efficient construction of green infrastructure and major transportation infrastructure. Experts from the Ministry of Finance said that PPP mode has become a new driving force for the low-carbon economy with its capital, management, and technological advantages. In this context, PPP has great potential under the development goals of the low-carbon economy.

Most studies have confirmed the economic value of PPP and point out that PPP has economic growth effect, not only in China [1–3], but also in other countries [4–6]. On the indirect side of the economic development, PPP can promote the quality and efficiency of infrastructure construction [7], improve employment and social welfare [8], drive the upgrading of industrial structure [9], and achieve higher-level urbanization [10]. In terms of spatial research, Cai's empirical study [6] found that PPP had a significant positive spatial spillover effect on the economic growth of the Belt and Road countries. Chen [11] confirmed the positive spatial spillover effect of PPP on regional economic development in China. By comparing the economic consequences of PPP with the traditional mode, some studies found that PPP applied in transportation infrastructure had more positive economic impacts than other fields [12], and PPP had a stronger promotion effect on transportation infrastructure investment efficiency than single government investment [13]. Chotia and Rao [5] compared the impact of PPP and single investment mode on economic development in India and found that only the PPP mode had significant economic growth effect. About PPP and carbon emissions, some studies pointed out that transportation PPP investment had certain positive effects on reducing carbon emissions from transportation industry [14]; and PPP could play an important role in low-carbon development by supporting green infrastructure [15]. However, Yao et al. [16] and Pei et al. [17] indicated that PPP was not a “panacea”, and it could bring more efficiency only when certain conditions are met. To sum up, few studies have considered the impact of the PPP mode on economic growth from the perspective of low-carbon development. Transportation PPP investment links the transportation industry, ESG investment, and social cooperation in one, which embodies diversified economic attributes. According to the existing findings, the efficiency advantages, economic growth effects of PPP, and its role in low-carbon development imply that it may play an active role in the low-carbon economy. Based on the green sustainable development concept and trend, it is necessary and worthy to connect carbon emissions with economic growth and investigate the impact of transportation PPP investment on the low-carbon economy.

On these grounds, this paper uses hand-collected, unique data of 276 cities in China from 2006 to 2018 as samples, based on the evaluation of the level and efficiency of low-carbon economic development in China, and empirically examines the impact of transportation PPP investment on China's low-carbon economic development from the diversified dimensions of the overall effect, spatial spillover effect, heterogeneous effect, mediating effect, lagged effect, and PPP projects characteristics. The main contributions of this study include revealing the relationship between transportation PPP investment and the low-carbon economy for the first time, which enriches the existing research on the economic consequences of PPP and confirms its profound influence and practical value; this provides empirical evidence and a point of reference for encouraging the widespread application of PPP in transportation infrastructure so that it may play a more effective and sustainable role in low-carbon economic development. For other countries, this paper may provide some valuable points of reference and a basis for them to apply or innovate PPP modes in the field of transportation infrastructure or other fields seeking to support low-carbon economic development.

The paper is organized as follows: the theoretical analysis is presented in Section 2. The data, variables, and model are introduced in Section 3. Section 4 presents the analyses of the evaluation of China's low-carbon economy, and the empirical analyses of the impact of transportation PPP investment on the low-carbon economy. Section 5 explains and discusses the findings. Section 6 presents the conclusion and enlightenments.

2. Theoretical Analysis

2.1. Transportation PPP Investment and Low-Carbon Economic Development

The low-carbon economy is a comprehensive and multi-objectives system including the multivariance of economic, ecological, social, management, and institutional elements with the goal of realizing higher economic growth with lower carbon emissions, which is driven by various factors of industrial upgrading, technological innovation, institutional change, resource allocation, effective investment, and so on. Therefore, all factors that can affect economic growth and carbon emissions will affect the low-carbon economy. Firstly, through the investment multiplier effect, PPP can stimulate domestic demand and expand the effective supply of transportation infrastructure to consolidate the endogenous foundation for low-carbon economic development [9]. Secondly, by the connectivity of transportation infrastructure under massive PPP investment, the high-end production factors such as management, technology, and knowledge can be allocated in a wider range of contexts. Furthermore, PPP introduces a marketization mechanism to optimize resource allocation, whose application in transportation infrastructure can conspicuously reduce the flow and use costs of production factors and improve resource allocation efficiency [18] to reduce the resources required by unit economic output in the process of economic development [19] thus forming the overall effect of energy conservation and emissions reduction throughout society [20]. Moreover, through PPP, large-scale construction of all kinds of transportation infrastructure can provide an indispensable carrier foundation for the upgrading of industrial structures, the progress of new urbanization and technological innovation of enterprises [10,21], thus promoting the improvement of various links in the low-carbon economy. The PPP mode can not only introduce abundant funds from social capital, but also simultaneously introduce their experience, technology, and knowledge [22] to achieve higher quality operations of transportation infrastructure, thus contributing to the construction of green transportation systems. Besides, under the mutual restriction of government and social capital, the downsides of government corruption and profit-seeking by social capital have also been alleviated by the governance mechanism of PPP [23,24], which will promote the sustainability and coordination between social benefits and economic benefits.

2.2. Spatial Spillover Effect of Transportation PPP Investment

Transportation infrastructure has the characteristics of networking and externality. It can break the spatial and temporal distance between each geographical space and connect it into a complete whole, thus speeding up the free flow of economic elements among regions and further changing the regional population distribution, industrial agglomeration, and economic space of cities. Moreover, transportation infrastructure has a strong effect of gathering elements and resources around and along its routes, thus making economic development present the spatial characteristics of agglomeration and scale. Therefore, transport PPP investment, as an important source of transport infrastructure construction, generates spatial spillover effect through expanding the supply scale, improving the spatial layout, and optimizing the structure of transportation infrastructure. According to economic theory, the externality of infrastructure roots in its public goods attribute, which can be further divided into positive externalities and negative externalities. The stronger externalities of transportation infrastructure compared to other forms of infrastructure have been widely supported by studies but whether it is positive or negative has not been unified. Zhang [25] pointed out that transportation infrastructure had an overall positive external effect on regional economic growth in China, but there was also evidence to show a negative or inapparent effect [26]. Furthermore, there are differences in the externalities of different types of transportation infrastructure [27]. From the perspective of PPP mechanism, transportation infrastructure invested through PPP is more efficient [7,28] and can bring a greater positive economic impact than traditional modes [12]. Therefore, it is reasonable to consider that transportation PPP investment can produce positive spatial spillover effect in general.

2.3. Mediating Effect of Industrial Structure on PPP and the Low-Carbon Economy

In the current process of industrialization in China, the unreasonable industrial structure and the development mode of high input, high pollution, and low output of the secondary industry will have adverse effects on the sustainability of a low-carbon economy. The transformation of the industrial structure, especially the decline of the proportion of the secondary industry, is an effective way to reduce carbon emissions and promote economic sustainability [29]. As a result, accelerating the dominance of the tertiary industry in GDP has become China's long-term development vision. Transportation infrastructure is a vital carrier for the development of the modern industrial system, its efficient construction and operation construction by PPP mode is a significant source for ensuring large-scale supply of transportation infrastructure and optimizing regional transportation connectivity, which can improve the spatial flow and reasonable allocation of production factors among different industrial sectors so as to promote the upgrading of regional industrial structures [9]. Additionally, the tertiary industry can benefit more from the improvement of transport infrastructure due to more convenient and less costly exchange of advanced production factors such as knowledge and technology [30]. On these grounds, this paper considers that there is a chain relationship between transportation PPP investment and the low-carbon economy, that is, PPP can promote the upgrading of industrial structure, thus further driving low-carbon economic development.

2.4. Heterogeneity of Transportation PPP Investment in Different Subsectors

Different transportation infrastructures have different investment attributes and economic consequences. Most studies have shown that railway and airport infrastructure play a stronger role in driving regional economic integration through its higher transportation efficiency and more complete network system [31,32]. As the basis for connectivity and accessibility of transportation network and the field with the largest number of PPP projects, road infrastructure has significant economic growth effect and positive spatial spillover effect [33], while its spatial spillover effect is weaker than that of railways [34]. Additionally, a subway is an intra-city infrastructure which has positive externality, manifesting as the value-added effect of commerce and land along the line to promote urban economic development [35,36]. Furthermore, PPP investment in different transportation subsectors will also generate different effects on resource allocation, industrial transformation, and economic agglomeration, which are highly correlated with the differentiated nature, function, and sphere of transportation infrastructure.

2.5. Lagged Effect of Transportation PPP Investment

The lagged effect reveals the time dynamic correlation between variables and is an important aspect of judging sustainability. Transportation PPP investment is a long-term investment, which is reflected in the long-term attribute of return on investment, the long franchise period of PPP projects, and lasting functionality of transportation infrastructure. Due to the inertia of economic activities, the connection between economic indicators tends to continue and delay, thus forming a hysteresis in time. These determine the lagged effect of transportation PPP investment on the low-carbon economy, which conforms to economic law. According to the influencing mechanism of PPP on the low-carbon economy, in addition to the immediate impact, PPP will indirectly affect many economic elements including the industrial structure, technological innovation, resource allocation, and so on; these effects are not apparent in the short term. Furthermore, the long-term operation of transportation infrastructure will continuously accumulate strength for economic development, which also takes time to prove. Consequently, it will be considered whether transportation PPP investment can play a stable and sustaining role in promoting the low-carbon economy.

2.6. Impact of Characteristic Factors of Transportation PPP Projects

In the institutional context of China, PPP has typical characteristics of the “Chinese style”, the most striking aspect of which is that the social capital participating in PPP projects is mainly state-owned enterprises [37]. State-owned enterprises have significant advantages in economic strength, technological innovation, and management ability, and are more resilient to risk which meets the demands of large-scale construction of transportation infrastructure and contributes more to the success of the PPP projects. Additionally, driven by the ESG investment idea, more and more listed companies take the initiative to participate in PPP projects, especially for transportation infrastructure projects related to the national economy and people’s livelihood. The participation of listed companies is not only the result of high support from the Chinese government, but also the vision of listed companies to fulfill social responsibilities and establish a good reputation, which has also triggered a positive market reaction and boosted their share prices [38]. This stimulates listed companies to make efforts to improve the performance of PPP projects. In addition, Moszoro [39] highlighted that public-private capital structure was the key factor affecting the performance of PPP projects and there should be an optimal capital structure of the public-private shareholdings to achieve maximum efficiency. Therefore, it is necessary to further investigate the impact of diversified PPP project characteristics to identify the project-level drivers of transportation PPP investment affecting the low-carbon economy, which can provide references for the effective design of PPP projects.

3. Data, Variables and Model

3.1. Data Sources

For measuring the level and efficiency of low-carbon economic development, the carbon emissions of 276 cities from 2006 to 2018 are obtained by calculation in this paper. The energy consumption data, energy carbon emission factors, and relevant standards used derive from the IPCC Guidelines for National Greenhouse Gas Inventories 2019 and the China National Standard “General rules for the calculation of the comprehensive energy consumption”. Urban economic data come from the China City Statistical Yearbook, National Economy and Social Development Statistics Bulletin of cities.

In empirically examining the impact of transportation PPP investment on low-carbon economic development, PPP investment data, including railway, road, airport, subway, and waterway, are hand-collected from the China Ministry of Finance Public-Private Partnerships Center and the World Bank Private Participation in Infrastructure Database. To ensure the validity and reliability of the analysis, only executed and successful PPP projects are used.

In the analysis of the impact of PPP project factors, project-level data are all hand-collected from the China Ministry of Finance Public-Private Partnerships Center, publicly available documents pertaining to each project, and the China Government Procurement Platform.

3.2. Research Variables

3.2.1. Explained Variables

A low-carbon economic level and efficiency are core explained variables. The former is measured by carbon productivity, that is GDP produced per unit of carbon dioxide emitted. The latter is the ratio between actual economic output and maximum output under the given factors input in the development of low-carbon economy, which is calculated by the production model. The combination of these two indicators can fully reflect the benefits and efficiency of low-carbon economic development.

The low-carbon economic development level is calculated by Formula (1).

$$CG_{it} = GDP_{it} / CO_{2it} \quad (1)$$

In Formula (1), CG_{it} is the low-carbon economic development level of the city i in year t . GDP_{it} is the gross domestic product, which has been converted to a real value based on

the data from 2006. CO_{2it} is the total amount of carbon dioxide emissions. The calculation of total amount of carbon dioxide emissions is based on the general approach of Chinese scholars [40,41], taking the consumption of electricity, coal gas, liquefied petroleum gas, and raw coal in cities, multiplied by its corresponding carbon emission coefficient, and then summed.

Stochastic frontier analysis is adopted to measure the low-carbon economic efficiency of cities. Considering that carbon emissions are a kind of undesired output, regarding them as production input factor as important as capital and labor into the production model conforms to the dual goals of maximizing desired outputs and minimizing undesired outputs in the low-carbon economy [42,43]. Based on the C–D production function [44], and adding carbon emissions as input factor, according to the time-varying model principle proposed by Battese and Coelli [45], the basic measure model was constructed.

$$\ln GDP_{it} = \alpha_0 + \alpha_1 \ln C_{it} + \alpha_2 \ln K_{it} + \alpha_3 \ln L_{it} + v_{it} - u_{it} \quad (2)$$

In the C–D production function, the output elasticity of each input factor is a fixed constant, and the substitution elasticity obeys the assumption of constant return to scale, which is not in line with economic reality [46]. A trans-log production function overcomes this drawback and more accurately confirms to the economic reality [47]. Therefore, referring to the general form of the trans-log production function under multiple inputs, based on Formula (2), the trans-log production model was constructed.

$$\ln GDP_{it} = \alpha_0 + \alpha_1 \ln C_{it} + \alpha_2 \ln K_{it} + \alpha_3 \ln L_{it} + \alpha_4 t + \alpha_5 t^2 + \alpha_6 \ln K_{it} \ln L_{it} + \alpha_7 \ln K_{it} \ln C_{it} + \alpha_8 \ln L_{it} \ln C_{it} + \alpha_9 (\ln C_{it})^2 + \alpha_{10} (\ln K_{it})^2 + \alpha_{11} (\ln L_{it})^2 + \alpha_{12} (\ln C_{it})t + \alpha_{13} (\ln K_{it})t + \alpha_{14} (\ln L_{it})t + v_{it} - u_{it} \quad (3)$$

In Formulas (2) and (3), GDP_{it} is the economic output. C_{it} represents the carbon emissions. K_{it} is the capital input, measured by fixed asset investment, which has been converted to a real value based on the data from 2006. L_{it} is the labor input, measured by the labor force population. α_1 , α_2 , and α_3 respectively represent the output elasticity of carbon emissions, capital, and labor. $v_{it} - u_{it}$ is a composite error term.

$$u_{it} = e^{-\eta(t-T)} u_i \quad (4)$$

In Formula (4), η is a time-varying parameter, for which a value greater than 0 indicates that efficiency tends to improve over time.

Low-carbon economic efficiency is defined as Formula (5).

$$CE_{it} = e^{-u_{it}} \quad (5)$$

In Formula (5), CE_{it} is the low-carbon economic efficiency of the city i in year t . When $u = 0$ and $CE = 1$, the individual actual output is equal to the maximum output; this is the state of optimal efficiency. When $u > 0$ and $0 < CE < 1$, this indicates the individual actual output is less than the maximum output and there is a state of efficiency loss.

3.2.2. Explanatory Variables

The core explanatory variable is transportation PPP investment, which is measured by the total amount of transportation PPP investment, including railway, road, airport, subway, and waterways in a city for a year. The characteristic factors of PPP projects are used to further explore the impact on the low-carbon economy at the PPP projects level. Based on data availability, this paper ultimately takes the franchise period, government shareholding proportion, whether social capital is a state-owned enterprise, whether social capital is a listed company, the number of industries involved in the social capital, and investment return mechanism of the project as the explanatory variables.

3.2.3. Mediating Variables

According to the theoretical analysis, there may be a chain relationship between PPP and the low-carbon economy through the upgrading of the industrial structure. This paper uses industrial structure supererogation to measure industrial transformation and upgrading. The upgrading of industrial structure should not only reflect the structural optimization of the contribution of each industry to GDP, but also reflect the improvement of labor productivity of each industry [48]. On this basis, the calculation formula was constructed.

$$IS_{it} = \sum_{m=1}^3 Y_{it,m} \times LP_{it,m}, m = 1, 2, 3 \quad (6)$$

In Formula (6), IS_{it} is industrial structure supererogation of the city i in year t . $Y_{it,m}$ represents the proportion of each industry within the GDP. $LP_{it,m}$ is the labor productivity of each industry; that is, divide each industry's added value of GDP by the proportion of its employment in total labor force. M 1, 2, and 3 stand for the primary, secondary, and tertiary industries, respectively.

3.2.4. Control Variables

Referring to relevant studies [43,49], this paper takes the economic base, fiscal self-sufficiency rate, degree of government intervention, opening to the outside world, and population size as control variables. The meaning and calculation, and descriptive statistics of all research variables are shown in Tables 1 and 2, respectively.

Table 1. Meaning and calculation of variables.

Variables	Meaning	Calculation
GDP	Gross domestic product	Take logarithm
C	Carbon dioxide emissions	Take logarithm
K	Fixed assets investment	Take logarithm
L	Labor force population	Take logarithm
CG	Low-carbon economic development level	Divide GDP by carbon emissions
CE	Low-carbon economic efficiency	Use SFA method
PPP	Transportation PPP investment	Take logarithm
FRP	Franchise period in year	Sum of construction and operation periods
GSP	Government shareholding proportion	Divide government share by total share of PPP project companies
SOE	Whether social capital is state-owned	State-owned = 1, otherwise 0
LTE	Whether social capital is listed	Listed = 1, otherwise 0
SIN	Number of industries in the social capital	Sum of industries involved in a PPP project
IEM	Investment return mechanism	Government payment = 1, government subsidy = 2, user payment = 3
IS	Industrial structure supererogation	Use Formula (6)
PG	GDP per capita	Divide GDP by population size
FS	Fiscal self-sufficiency rate	Divide fiscal revenue by expenditure
GI	Government intervention degree	Divide fiscal revenue by GDP
OP	Opening to the outside world	Divide total import and export by GDP
PO	Population size	Take logarithm

3.3. Model Specification

3.3.1. Model for Examining the Overall Impact of Transportation PPP Investment

This paper first sets up Formula (7) to investigate the overall impact of transportation PPP investment on the low-carbon economy from the dual perspectives of benefits and efficiency. According to the results of the Hausman test, combined with the nature and characteristics of low-carbon economy, the two-factor fixed effects model was constructed.

$$CG_{it}(CE_{it}) = \alpha_0 + \alpha_1 PPP_{it} + \alpha_2 PG_{it} + \alpha_3 FS_{it} + \alpha_4 GI_{it} + \alpha_5 OP_{it} + \alpha_6 PO_{it} + \gamma_i + \delta_t \quad (7)$$

In Formula (7), CG_{it} and CE_{it} are the low-carbon economic level and efficiency, respectively; PPP_{it} is transportation PPP investment (its coefficient measures the net effect of PPP

on the low-carbon economy); i represents the city, and t represents the year; and γ_i , and δ_t represent the fixed effect of city and year, respectively.

Table 2. Descriptive statistics of variables.

Variables	Observations	Mean	Sd	Min	Max
GDP	3588	15.702	0.921	13.160	18.686
C	3588	3.031	0.780	0.613	5.441
K	3588	15.831	1.069	12.709	19.045
L	3588	12.756	0.833	10.648	16.105
CG	3588	0.648	0.390	0.087	2.690
CE	3588	0.369	0.148	0.083	1.000
PPP	3588	1.580	4.166	0.000	16.604
FRP	778	19.704	8.631	8	45
GSP	757	0.162	0.183	0.000	1.000
SOE	751	0.872	0.334	0	1
LTE	753	0.206	0.405	0	1
SIN	749	1.559	0.739	1	4
IEM	770	1.566	0.596	1	3
IS	3588	0.302	0.173	0.045	4.026
PG	3588	9.855	0.600	7.926	11.808
FS	3588	0.480	0.231	0.054	1.541
GI	3588	0.071	0.028	0.019	0.238
OP	3588	0.203	0.391	0.000	8.134
PO	3588	5.868	0.692	2.869	8.131

3.3.2. Model for Examining the Spatial Spillover Effect of Transportation PPP Investment

The spatial relationship between variables is not considered in Formula (7), which may lead to potential bias in parameter estimations and not enough in-depth conclusions. The spatial effect is an indispensable analytical perspective which can further extend the relationship between variables to regional interaction, thus providing references for regional integration development. The spatial weight matrix is the basis of spatial study, the scientific selection of which directly affects the accuracy of the findings [50]. The spatial weight matrices can be divided into three basic types: the geographic adjacency matrix, geographic distance matrix, and economic distance matrix. In view of the physical properties of transportation infrastructure interconnection and characteristics of neighborhood cooperation of the PPP mode, this paper selects the geographic adjacency matrix to investigate the spatial correlation between transportation PPP investment and the low-carbon economy, and defines the elements in the matrix as whether two cities are adjacent to each other (adjacent = 1, otherwise 0). Through these calculations, the 276×276 dimensional matrix is obtained. On the basis of Formula (7), the spatial Durbin model was constructed.

$$CG_{it}(CE_{it}) = \rho \sum_{j=1}^{276} W_{ij} \times CG_{jt}(CE_{jt}) + \alpha_1 PPP_{it} + \sum \alpha_k Control_{it} + \beta_1 \sum_{j=1}^{276} W_{ij} \times PPP_{jt} + \sum \beta_k \sum_{j=1}^{276} W_{ij} \times Control_{jt} + \gamma_i + \delta_t \quad (8)$$

In Formula (8), ρ is the spatial autocorrelation coefficient, showing the spatial dependence between urban low-carbon economies; W represents the 276×276 dimensional geographic adjacency matrix; α and β measure the impact of variables on the low-carbon economic development of the local and neighboring cities, respectively; and β_1 measures the spatial spillover effect of transportation PPP investment on the low-carbon economy.

3.3.3. Model for Examining the Mediating Effect of Industrial Structure Supererogation

In order to verify the mediating effect of industrial structure supererogation on transportation PPP investment and low-carbon economic development, the stepwise regression models were constructed.

$$IS_{it} = b_0 + b_1 PPP_{it} + b_2 PG_{it} + b_3 FS_{it} + b_4 GI_{it} + b_5 OP_{it} + b_6 PO_{it} + \gamma_i + \delta_t \quad (9)$$

$$CG_{it}(CE_{it}) = c_0 + c_1 PPP_{it} + c_2 IS_{it} + c_3 PG_{it} + c_4 FS_{it} + c_5 GI_{it} + c_6 OP_{it} + c_7 PO_{it} + \gamma_i + \delta_t \quad (10)$$

In Formulas (9) and (10), b_1 measures the impact of transportation PPP investment on industrial structure supererogation. c_2 measures the impact of industrial structure supererogation on the low-carbon economy. If these two coefficients are both significant, it can be inferred that the mediating effect holds. If one is not significant, further tests are required.

For further exploring whether there is a spatial relationship of the mediating effect, the spatial stepwise regression models were further constructed based on Formula (8).

$$IS_{it} = \rho \sum_{j=1}^{276} W_{ij} \times IS_{jt} + b_1 PPP_{it} + \sum b_k Control_{it} + \varepsilon_1 \sum_{j=1}^{276} W_{ij} \times PPP_{jt} + \sum \varepsilon_k \sum_{j=1}^{276} W_{ij} \times Control_{jt} + \gamma_i + \delta_t \quad (11)$$

$$CG_{it}(CE_{it}) = \rho \sum_{j=1}^{276} W_{ij} \times CG_{jt}(CE_{jt}) + c_1 PPP_{it} + c_2 IS_{it} + \sum c_k Control_{it} + \theta_1 \sum_{j=1}^{276} W_{ij} \times PPP_{jt} + \theta_2 \sum_{j=1}^{276} W_{ij} \times IS_{jt} + \sum \theta_k \sum_{j=1}^{276} W_{ij} \times Control_{jt} + \gamma_i + \delta_t \quad (12)$$

In Formulas (11) and (12), ε_1 measures the spatial spillover effect of transportation PPP investment on industrial structure supererogation. θ_2 measures the spatial spillover effect of industrial structure supererogation on the low-carbon economy. If these two coefficients are both significant, the mediating effect can be further interpreted as the spatial interaction mechanism that transportation PPP investment can affect the upgrading of regional industrial structure, thus affecting regional low-carbon economic development.

3.3.4. Model for Examining the Impact of Characteristics of Transportation PPP Projects

In order to explore the impact of PPP project characteristics on the low-carbon economy, according to the selected project factors, the model was constructed.

$$CG(CE) = \alpha_0 + \alpha_1 FRP + \alpha_2 GSP + \alpha_3 SOE + \alpha_4 LTE + \alpha_5 SIN + \alpha_6 IEM \quad (13)$$

In Formula (13), SOE is a dummy variable, where SOE = 1 indicates social capital includes state-owned enterprises; LTE is also a dummy variable, where LTE = 1 indicates that the social capital includes listed companies. IEM is a categorical variable, the return mechanism of PPP projects in China includes government payments, government subsidies, and user payments. This paper defines IEM = 1 for the government-payment mode, IEM = 2 for the government-subsidy mode, and IEM = 3 for the user-payment mode.

A typical feature of PPP projects in China is that state-owned enterprises are the main body of the social capital. In addition, the participation of listed companies in PPP has become a development trend in recent years, which is strongly supported by the Chinese government. In this context, this paper further verifies the impact of state-owned enterprises' and listed companies' participation under different PPP project scales. The model to examine the moderating effect was constructed.

$$CG(CE) = \alpha_0 + \alpha_1 SOE + \alpha_2 PPP + \alpha_3 (SOE \times PPP) + \alpha_4 FRP + \alpha_5 GSP + \alpha_6 LTE + \alpha_7 SIN + \alpha_8 IEM \quad (14)$$

$$CG(CE) = \alpha_0 + \alpha_1 LTE + \alpha_2 PPP + \alpha_3 (LTE \times PPP) + \alpha_4 FRP + \alpha_5 GSP + \alpha_6 SOE + \alpha_7 SIN + \alpha_8 IEM \quad (15)$$

In Formulas (14) and (15), PPP represents the investment scale of a single PPP project; SOE $\times$ PPP and LTE $\times$ PPP are the interaction terms; and the coefficients of these two variables measure the moderating effect of PPP project investment scale on state-owned enterprise and listed company participation and the low-carbon economy. The project investment scale in the interaction term was mean-centralized in order to overcome the multicollinearity.

4. Empirical Analysis

4.1. Evaluation and Analysis of China's Low-Carbon Economic Development

Formulas (1)–(5) are used to measure the low-carbon economic development level and efficiency of 276 cities from 2006 to 2018. As the results cover 3588 pieces of data, it is impossible to display all the results in detail. Consequently, this paper focuses on the analysis of the development trend, regional differences, and urban differences. These results are shown in Tables 3–5, respectively. See Figure 1 for the scatter plot of the low-carbon economic development level and efficiency.

Table 3. Low-carbon economic development in China from 2006 to 2018.

Year	Level	Efficiency	Correlation Coefficient
2006	0.377	0.351	0.847
2007	0.424	0.354	0.844
2008	0.476	0.357	0.851
2009	0.490	0.360	0.856
2010	0.539	0.363	0.857
2011	0.582	0.366	0.872
2012	0.636	0.369	0.871
2013	0.691	0.372	0.887
2014	0.726	0.375	0.883
2015	0.810	0.378	0.859
2016	0.834	0.381	0.837
2017	0.882	0.384	0.847
2018	0.952	0.387	0.833

Note: The level and efficiency of the low-carbon economy are the average value, same below.

Table 4. Low-carbon economic development of different regions in China.

Region	Low-Carbon Economic Level	Low-Carbon Economic Efficiency
East	0.766	0.499
Middle	0.590	0.334
West	0.569	0.295
North	0.517	0.360
South	0.729	0.400

Table 5. Low-carbon economic development under classification of cities in China.

Criterion	Classification	Level	Efficiency
Provincial administrative divisions	Municipality directly under central government	1.193	0.601
	Provincial capital	0.854	0.478
	Non-provincial capital	0.617	0.353
Comprehensive strength of cities	First-tier	1.917	0.877
	New first-tier	1.041	0.594
	Second-tier	0.805	0.492
	Third-tier	0.639	0.385
	Fourth-tier	0.625	0.356
	Fifth-tier	0.478	0.252

Note: The classification of cities comes from the China City Statistical Yearbook and China's authoritative data platform "CBN Data".

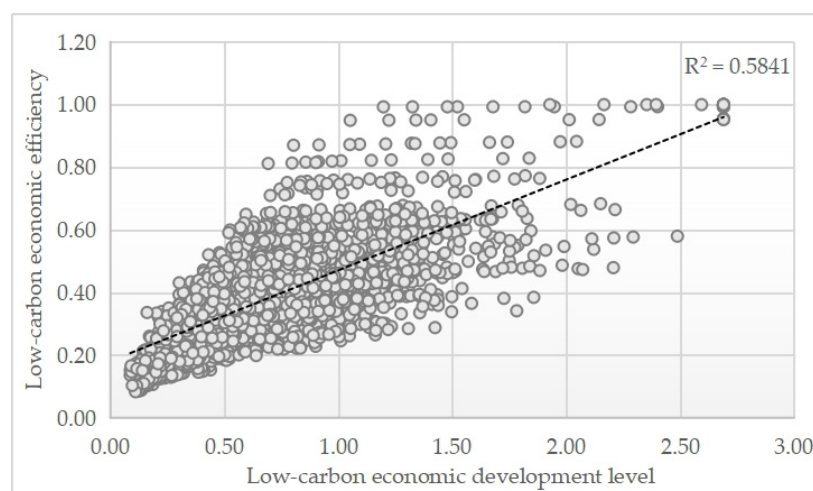


Figure 1. Scatter plot of low-carbon economic development level and efficiency.

From 2006 to 2018, China's low-carbon economy shows a positive development trend which is reflected in the sustaining improvement of both benefits and efficiency. Combined with Table 2, the average low-carbon economic efficiency is only 0.369 over the 13 years, which is far from the optimal efficiency (1.000), indicating that the efficiency loss is still prominent in China's low-carbon economy and problems such as the low efficiency of resource allocation and unreasonable input structures need to be solved urgently. From the perspective of the coordination of development, the correlation coefficient between the level and efficiency of the low-carbon economy is 0.764, indicating that there is a strong positive correlation between the two indicators; the coefficients of each year show a dynamic tendency of fluctuation, but always maintain a high degree of association. These results manifest the connotation of sustainability that its benefits and efficiency are coordinated and unified in the process of achieving a low-carbon economy in China.

China's regional low-carbon economic development generally presents a distribution law of "high in the east and low in the west, high in the south and low in the north", revealing remarkable regional development discrepancy and imbalance, which accords with China's economic reality. The eastern region is the most economically developed region in China, it relies on its advantageous geographical location, strong innovation ability, abundant financial funds, and national policy support to take the lead to achieve high-quality low-carbon economic development. While western China is restricted by factors such as its environment, infrastructure, and technology, whose development pattern is less advanced. This results in inefficient resource utilization and high pollutant emissions, which impedes its sustainable development of a low-carbon economy. Furthermore, the difference between the north and south is mainly related to the industrial structure of each region. Heavy industry is concentrated in northern China, which inevitably leads to high pollution and carbon emissions, while the south of China is dominated by light industry and the service industry. It can be inferred that industrial structure is an important factor affecting the development of low-carbon economy.

It can be found that there are obvious differences in the development of the low-carbon economy in different types of cities. In the subdivisions of provincial administrative divisions, both the level and efficiency of the low-carbon economy in municipalities directly under central government are higher than provincial capital and higher than non-provincial capital. In the subdivisions of the comprehensive strength of cities, both the level and efficiency of low-carbon economy successively decline from first-tier to fifth-tier cities. The reason lies in that the economic foundation, political status, and comprehensive strength of different cities vary greatly, which results in wide differences in urban development ability and conditions. For instance, first-tier cities have the most favorable position in every aspect and there is no doubt that their development is the fastest.

4.2. Overall Impact of Transportation PPP Investment on the Low-Carbon Economy

Before empirical analysis, it is necessary to conduct the unit root test on variables to judge their stationarity in the panel sequence, which is an important basis to ensure the reliability of results. In this paper, the LLC test and IPS test are used in combination to examine the stationarity of the data, and the results are shown in Table 6.

Table 6. Unit root test for core variables.

Variables	LLC Test		IPS Test	
	Adjusted t	p-Value	Z-t-Tilde-Bar	p-Value
CG	−6.745	0.000	−22.899	0.000
CE	−18.728	0.000	−18.307	0.000
PPP	−13.898	0.000	−18.109	0.000
IS	−7.437	0.000	−15.557	0.000
PG	−6.826	0.000	−17.747	0.000
FS	−20.075	0.000	−10.073	0.000
GI	−11.665	0.000	−1.534	0.063
OP	−21.626	0.000	−15.782	0.000
PO	−7.496	0.000	−3.643	0.000

The LLC test and IPS test for core variables both reject the null hypothesis that the panel contains the unit root and consider panel data sequence to be stationary. Therefore, this paper uses raw data for regression. Additionally, Formula (7) is used to examine the overall impact of transportation PPP investment on low-carbon economy. The results are shown in Table 7.

Table 7. Overall impact of transportation PPP investment on the low-carbon economy.

Variables	CG		CE	
PPP	0.005 *** (6.85)	0.004 *** (5.98)	0.001 *** (4.16)	0.001 *** (3.24)
PG		0.209 *** (15.06)		0.001 *** (6.26)
FS		0.286 *** (6.44)		0.002 *** (3.63)
GI		−1.590 *** (−6.83)		−0.009 *** (−2.94)
OP		−0.081 *** (−7.87)		0.001 *** (10.75)
PO		0.553 *** (14.86)		−0.002 *** (−4.20)
Year	Control	Control	Control	Control
City	Control	Control	Control	Control
N	3588	3588	3588	3588
R ²	0.681	0.732	0.179	0.741

Note: The values in parentheses are t statistics; *** indicates statistical significance of 99%.

Regardless of whether control variables are added, transportation PPP investment is always significantly positively correlated with both the level and efficiency of the low-carbon economy at the statistical level of 1%, showing that transportation PPP investment promotes the low-carbon economic development in China from 2006 to 2018, which is manifested as the dual improvement effects of benefits and efficiency. This has laid a solid foundation for further study on the spatial spillover effect of PPP. The results of the control variables show that the economic base of cities is the core driving factor for low-carbon economic development. Besides, fiscal self-sufficiency, government intervention, opening to the outside world, and population size are also important factors affecting the low-carbon economy.

In order to mitigate the bias caused by endogeneity, referring to existing studies [51–53], this paper lags the core explanatory variable PPP by one period to take it as an instrumental variable to perform 2SLS regression. The results are shown in Table 8.

Table 8. 2SLS regression under the instrumental variable.

Variables	PPP	CG	PPP	CE
	First Stage	Second Stage	First Stage	Second Stage
PPP		0.033 *** (2.79)		0.001 ** (2.11)
IV	0.077 *** (3.76)		0.077 *** (3.76)	
PG	2.116 *** (5.11)	0.155 *** (4.70)	2.116 *** (5.11)	0.001 (0.75)
FS	−1.451 (−1.10)	0.326 *** (5.29)	−1.451 (−1.10)	0.003 *** (4.45)
GI	17.844 ** (2.57)	−2.169 *** (−5.76)	17.844 ** (2.57)	−0.017 *** (−3.76)
OP	−0.213 (−0.70)	−0.064 *** (−4.67)	−0.213 (−0.70)	0.001 *** (8.01)
PO	0.227 (0.21)	0.532 *** (10.84)	0.227 (0.21)	−0.002 *** (−2.83)
Year	Control	Control	Control	Control
City	Control	Control	Control	Control
N	3312	3312	3312	3312
R ²	0.399	0.531	0.399	0.568
F statistic	117.64		117.64	

Note: The values in parentheses are t statistics; ***, ** respectively indicate statistical significance of 99%, 95%. The results of the first-stage regression show that IV is positively correlated with PPP at the 1% significance level; and the F statistic is 117.64, which is greater than the critical value of 10.00 for identifying weak instrumental variables, indicating that the instrumental variable selected is effective. In the second stage, PPP is still significantly positive with CG and CE at the statistical level of 1% and 5%, respectively, which is consistent with the above results. Accordingly, it can be assumed that the basic results of this paper are relatively robust and valid after controlling for endogeneity.

4.3. Spatial Spillover Effect of Transportation PPP Investment on the Low-Carbon Economy

Before examining the spatial spillover effect of transportation PPP investment on low-carbon economy, it is necessary to verify the spatial autocorrelation of low-carbon economy with Moran's Index. The results are shown in Table 9.

Table 9. Spatial autocorrelation of the low-carbon economy.

Year	CG		CE	
	Moran's I	Z	Moran's I	Z
2006	0.127 ***	21.09	0.130 ***	21.14
2007	0.123 ***	20.54	0.130 ***	21.16
2008	0.120 ***	19.91	0.130 ***	21.18
2009	0.120 ***	19.87	0.130 ***	21.20
2010	0.121 ***	20.11	0.131 ***	21.21
2011	0.109 ***	17.98	0.131 ***	21.23
2012	0.109 ***	17.99	0.131 ***	21.25
2013	0.113 ***	18.65	0.131 ***	21.26
2014	0.126 ***	20.61	0.131 ***	21.28
2015	0.143 ***	23.25	0.131 ***	21.29
2016	0.161 ***	25.99	0.131 ***	21.31
2017	0.167 ***	26.93	0.131 ***	21.33
2018	0.173 ***	27.89	0.132 ***	21.34

Note: *** indicates statistical significance of 99%.

Moran's I of both CG and CE from 2006 to 2018 is always significantly positive, which shows that there is a strong spatial autocorrelation of the low-carbon economy. Therefore, it is meaningful to extend this study from the traditional perspective to the spatial perspective. Formula (8) is used to explore the spatial relationship between transportation PPP investment and the low-carbon economy; the results of the direct effect, indirect effect, and overall effect are summarized as Table 10.

Table 10. Spatial spillover effect of transportation PPP investment on the low-carbon economy.

Variables	CG			CE		
	Direct	Indirect	Total	Direct	Indirect	Total
PPP	0.003 *** (4.81)	0.007 *** (3.14)	0.010 *** (3.74)	0.001 *** (3.46)	0.001 *** (2.61)	0.001 *** (3.37)
PG	0.140 *** (11.42)	0.102 *** (2.96)	0.242 *** (6.47)	0.001 *** (5.38)	−0.001 (−0.49)	0.001 ** (2.54)
FS	0.278 *** (7.70)	0.102 (0.84)	0.380 *** (2.76)	0.002 *** (3.44)	−0.001 (−0.55)	0.001 (0.97)
GI	−1.895 *** (−10.30)	0.706 (1.08)	−1.189 (−1.58)	−0.007 *** (−2.67)	0.004 (0.72)	−0.003 (−0.40)
OP	−0.062 *** (−7.04)	−0.180 *** (−4.90)	−0.242 *** (−5.75)	0.002 *** (10.28)	0.003 *** (9.95)	0.005 *** (11.98)
PO	0.448 *** (13.67)	0.229 * (1.74)	0.677 *** (4.59)	−0.002 *** (−3.62)	−0.001 (−0.79)	−0.003 ** (−2.05)
ρ		0.613 *** (42.17)			0.320 *** (15.21)	
Year		Control			Control	
City		Control			Control	
N		3588			3588	
R ²		0.546			0.439	

Note: The values in parentheses are t statistics; ***, **, * respectively indicate statistical significance of 99%, 95%, and 90%.

The regression coefficients of the direct, indirect, and total effect between PPP and CG, and PPP and CE are always significantly positive, showing that transportation PPP investment has significant and positive spatial spillover effect on the low-carbon economy, which is manifested as the double spatial effects of both benefits and efficiency improvement. Namely, transportation PPP investment can not only promote local low-carbon economic development, but also have a positive impact on neighboring cities. Moreover, by comparing the significance of the coefficients, it can be seen that the coefficients are more significant under the direct effect, implying that urban low-carbon economic development is mainly driven by factors internal to the city itself.

4.4. Mediating Effect of Industrial Structure Supererogation

The premise of testing the mediating effect is that transportation PPP investment has a significant impact on low-carbon economic development, which has been verified in Section 4.2. Therefore, Formulas (9) and (10) are used to examine the overall mediating effect of industrial structure supererogation on transportation PPP investment and the low-carbon economy. The results are shown in Table 11.

There is a significant positive correlation between PPP and IS at the 1% statistical level, showing that transportation PPP investment can promote the upgrading of the industrial structure from the traditional mode to being tertiary-industry dominated. Furthermore, IS is also positively correlated with CG and CE, indicating that industrial structure supererogation can also promote low-carbon economic development. Accordingly, it can be considered that there is a chain relationship between transportation PPP investment and the low-carbon economy through the upgrading of the industrial structure. Formulas (11) and (12) are used to further explore the mediating effect of industrial struc-

ture supererogation on transportation PPP investment and the low-carbon economy from the spatial perspective. The results are shown in Table 12.

Table 11. Overall mediating effect of industrial structure supererogation.

Variables	IS	CG	CE
PPP	0.004 *** (5.59)	0.003 *** (5.58)	0.001 *** (3.08)
IS		0.069 *** (3.99)	0.001 * (1.84)
PG	0.043 *** (3.08)	0.206 *** (14.86)	0.001 *** (6.17)
FS	0.103 ** (2.29)	0.279 *** (6.29)	0.002 *** (3.57)
GI	−0.334 (−1.42)	−1.567 *** (−6.74)	−0.009 *** (−2.90)
OP	−0.008 (−0.75)	−0.081 *** (−7.84)	0.001 *** (10.77)
PO	0.039 (1.03)	0.550 *** (14.82)	−0.002 *** (−4.23)
Year	Control	Control	Control
City	Control	Control	Control
N	3588	3588	3588
R ²	0.229	0.733	0.754

Note: The values in parentheses are t statistics; ***, **, * respectively indicate statistical significance of 99%, 95%, and 90%.

Table 12. Spatial mediating effect of industrial structure supererogation.

Variables	IS			CG			CE		
	Direct	Indirect	Total	Direct	Indirect	Total	Direct	Indirect	Total
PPP	0.003 *** (4.93)	0.005 *** (3.91)	0.008 *** (5.25)	0.002 *** (4.42)	0.005 *** (2.60)	0.007 *** (3.28)	0.001 *** (3.16)	0.001 ** (2.18)	0.001 *** (3.04)
IS				0.030 ** (2.16)	0.247 *** (4.77)	0.277 *** (4.68)	0.001 (0.69)	0.002 *** (3.63)	0.003 *** (3.50)
CV		Yes			Yes			Yes	
ρ		0.207 *** (9.62)			0.605 *** (40.99)			0.315 *** (14.90)	
Year		Control			Control			Control	
City		Control			Control			Control	
N		3588			3588			3588	
R ²		0.137			0.617			0.489	

Note: The values in parentheses are t statistics; ***, ** respectively indicate statistical significance of 99%, 95%; CV represents the set of control variables.

The spatial autocorrelation coefficient of IS is significantly positive (0.207), which confirms that the upgrading of the regional industrial structure is an integral, dynamic, and mutually promoting process. In addition to the direct effect, the indirect effect of PPP on IS is still significantly positive, showing that PPP can promote the industrial structure supererogation of the neighboring cities. Moreover, IS also has a significant positive indirect impact on CG and CE. All these reveal a deeper conclusion that the mediating effect has a broader scope of action, which is manifested as a spatial conduction mechanism; that is, transportation PPP investment can promote regional low-carbon economic development by promoting the industrial structure supererogation.

4.5. Heterogeneity Effect of Transportation PPP Investment on the Low-Carbon Economy

Based on the analysis of the overall effect and spatial spillover effect of PPP, this paper ulteriorly discusses the heterogeneous effects of transportation PPP investment in different subsectors on the low-carbon economy; Formulas (7) and (8) are used to examine

the heterogeneity in overall effect and spatial spillover effect. The results are shown in Tables 13 and 14, respectively.

Table 13. Industry heterogeneity in the overall effect of transportation PPP investment.

Subsectors	CG	CE
Road	0.003 *** (4.19)	0.001 *** (3.34)
Railway	0.010 *** (7.59)	−0.001 ** (−2.45)
Airport	−0.007 *** (−2.75)	0.001 (1.05)
Waterway	−0.001 (−0.42)	0.001 * (1.85)
Subway	0.009 *** (6.40)	−0.001 *** (−6.28)

Note: The values in parentheses are t statistics; ***, **, * respectively indicate statistical significance of 99%, 95%, and 90%; the results are after adding all control variables.

Table 14. Industry heterogeneity in the spatial spillover effect of transportation PPP investment.

Subsectors	CG			CE		
	Direct	Indirect	Total	Direct	Indirect	Total
Road	0.002 *** (2.81)	0.008 *** (3.26)	0.010 *** (3.43)	0.001 *** (3.89)	0.001 (0.39)	0.001 * (1.69)
Railway	0.007 *** (5.83)	0.019 *** (4.75)	0.026 *** (5.49)	−0.001 ** (−2.47)	0.001 ** (1.97)	0.001 (1.06)
Airport	−0.006 ** (−2.33)	−0.021 ** (−2.52)	−0.027 *** (−2.65)	0.001 (1.02)	−0.001 (−0.32)	0.001 (0.12)
Waterway	−0.001 (−0.51)	−0.002 (−0.37)	−0.003 (−0.44)	0.001 (1.44)	0.001 (1.56)	0.001 * (1.66)
Subway	0.009 *** (6.53)	0.005 (0.81)	0.014 ** (2.08)	−0.001 *** (−5.99)	−0.001 (−0.59)	−0.001 ** (−2.44)

Note: The values in parentheses are t statistics; ***, **, * respectively indicate statistical significance of 99%, 95%, and 90%; the results are after adding all control variables.

There is significant heterogeneity in the impacts of transportation PPP investment in different subsectors on the low-carbon economy. In general, road PPP has the strongest promotion effects on both low-carbon economic benefits and efficiency. As the most basic and extensive infrastructure of integrated transportation system, road infrastructure has become the first field in China to introduce social capital, with the largest number of projects and the largest scale of investment. By this same token, PPP has a stronger driving effect on road infrastructure, which effectively improves the quality and quantity of roads' construction and plays a key role in giving play to the interconnecting effect of road infrastructure and improving the overall efficiency of the regional transportation network. Additionally, railway PPP plays a more important role in driving the integrated development of regional low-carbon economies, which embodies the core value of railway infrastructure as a major economic artery in China. Although railways and subways have the characteristics of low-carbon transportation, their average investment scale is the largest and the public welfare of a subway is stronger, which will cause the asymmetry between input and output, thus weakening their contribution to the efficiency of the low-carbon economy. In addition, airport and waterway construction have higher requirements for geographical conditions, resulting in relatively few PPP projects compared to other fields. Consequently, the scale benefits of PPP investment in both fields on the low-carbon economy have not yet emerged. As an inner-city system, a subway does not have spatial spillover effect, which is consistent with the economic reality.

4.6. Lagged Effect of Transportation PPP Investment on the Low-Carbon Economy

Given the long franchise periods of transportation PPP projects and the sustainability of transportation infrastructure, the explanatory variable is lagged three periods to verify the lagged effect of transportation PPP investment on the low-carbon economy. The results are shown in Table 15.

Table 15. Lagged effect of transportation PPP investment on the low-carbon economy.

Variables	CG	CE
L1.PPP	0.003 *** (3.61)	0.001 ** (2.50)
L2.PPP	0.002 ** (2.08)	0.001 *** (2.96)
L3.PPP	0.002 (1.01)	0.001 *** (4.00)

Note: The values in parentheses are t statistics; ***, **, * respectively indicate statistical significance of 99%, 95%, the results are after adding all control variables.

On the whole, the positive impact of transportation PPP investment on China's low-carbon economy shows relatively strong continuity and stability, highlighting the connotation of economic sustainability of transportation PPP investment. In addition, lagged regression can effectively alleviate the endogeneity between variables, thus guaranteeing the reliability and validity of the research conclusions of this paper.

4.7. Impact of Characteristics of Transportation PPP Projects on the Low-Carbon Economy

Formula (13) is used to explore the impact of transportation PPP projects' characteristics on low-carbon economic development. The results are shown in Table 16.

Table 16. Impact of transportation PPP projects characteristics on the low-carbon economy.

Variables	CG	CE
FRP	−0.007 *** (−2.69)	−0.002 *** (−2.89)
GSP	−0.224 ** (−2.02)	−0.057 * (−1.68)
SOE	0.124 ** (2.36)	0.009 (0.58)
LTE	0.123 *** (2.81)	0.048 *** (3.57)
SIN	0.038 (1.55)	0.006 (0.73)
IEM	−0.010 (−0.27)	−0.001 (−0.05)
N	735	735

Note: The values in parentheses are t statistics; ***, **, * respectively indicate statistical significance of 99%, 95%, and 90%.

According to the regression results, it is found that franchise period, government shareholding proportion, and nature of the social capital (state-owned enterprise and listed company) are the main project-level factors affecting the low-carbon economy. Among them, FRP and GSP are negatively correlated with the low-carbon economy, while SOE and LTE are positively correlated. Given the public welfare nature of transportation infrastructure, most PPP projects cannot cover the huge costs with revenue during operation and require government payments or subsidies. Additionally, the longer the franchise period, the higher the value of government subsidies tends to be, which will result in fiscal unsustainability and other unsustainable factors. Furthermore, the higher the government's shareholding in the PPP project company, the stronger the government's intervention in the project operation and management, which may limit the full play of the advantages of

social capital endowment, thus affecting the performance of the project. The participation of state-owned enterprises and listed companies can bring more advanced technology, more scientific operation management experience, and more stable funding sources so as to ensure the efficient implementation of PPP projects.

Next, Formulas (14) and (15) are used to examine the moderating effect of PPP projects' investment scale on the effects of state-owned enterprise and listed company participation. The results are shown in Tables 17 and 18.

Table 17. Moderating effect of PPP projects scale on state-owned enterprises' participation.

Variables	CG	CE
SOE	0.150 *** (2.86)	0.015 (0.93)
PPP	0.033 ** (1.98)	0.014 *** (2.79)
SOE $\times$ PPP	0.077 *** (3.69)	0.020 *** (3.15)
CV	Yes	Yes
N	735	735

Note: The values in parentheses are t statistics; ***, ** respectively indicate statistical significance of 99%, 95%; CV represents the set of control variables.

Table 18. Moderating effect of PPP projects scale on listed companies' participation.

Variables	CG	CE
LTE	0.091 * (1.86)	0.042 *** (2.95)
PPP	0.062 *** (4.13)	0.023 *** (4.70)
LTE $\times$ PPP	0.006 (0.21)	−0.007 (−0.76)
CV	Yes	Yes
N	735	735

Note: The values in parentheses are t statistics; ***, * respectively indicate statistical significance of 99%, 90%; CV represents the set of control variables.

The regression coefficients of SOE $\times$ PPP are significantly positive while those of LTE $\times$ PPP are not significant, indicating that the investment scale of PPP projects has a moderating effect on the impact of state-owned enterprises. Namely, the participation of state-owned enterprises can play a more effective role in PPP projects with larger scales. The reason for this is that PPP projects with higher investment scale have higher risk and higher requirements for capital scale and stability. State-owned capital can act as a stabilizer to play a stronger leading role in these PPP projects, which is conducive to ensuring the smooth and efficient construction and operation of transportation infrastructure.

5. Discussion

5.1. The Promotion Effect of Transportation PPP Investment on the Low-Carbon Economy

The findings confirm the low-carbon economic advantages of transportation PPP investment and reveal the deeper implications: (1) the combination of carbon emissions and economic growth should be uniformly considered to analyze the effects of transportation PPP investment, which emphasizes that transportation PPP investment actually improves the productive capacity of the economy driven by carbon emissions rather than absolute carbon reduction. (2) There are various dimensions to measure the low-carbon economy, such as decoupling factors and low-carbon competitiveness. The reasons why this paper does not use these metrics are that they cannot directly reflect the results of low-carbon economy and are also not closely related to transportation PPP investment. The output-oriented indicators more accurately accord with the development goals of coordination of economic benefits and efficiency pursued by developing countries in the process of

realizing a low-carbon economy [54]. (3) The spatial spillover effect of transportation PPP investment is closely related to the spatial spillover of the economy itself, reflecting the spatial characteristics of economic factors. Moreover, most transportation PPP projects are jointly invested and constructed among regions, which highlights the economic development mode under interregional cooperation and constitutes the practical motivation of the spatial spillover effect of transportation PPP investment. To sum up, conclusions are in line with the reality of economic and social development in China, as well as the particularity and representativeness of PPP applied in the transportation industry.

5.2. Correctly Understanding the Economic Value of PPP for the Low-Carbon Economy

The positive effects of transportation PPP investment on the low-carbon economy in China are verified based on successfully implemented PPP projects. However, in practice, there are also a large number of failed or suspended transportation PPP projects because of failing to realize the expected value, wrong decisions by government, conflicts of interest, unreasonable estimates of returns, and so on. There is no doubt that these projects will lead to waste of resources and loss of value, which becomes the opposite of their original intention. This is a warning that the application of the PPP mode cannot guarantee the achievement efficiency and the economic value of PPP should be viewed rationally, especially for the transportation industry, where investment and risk are both high. As a result, it should attach great importance to strengthen the top-level design of PPP to prevent unfavorable factors and facilitate efficient cooperation under the conditions of a harmony of interests, reasonable transaction structure, effective government supervision, and risk allocation mechanism. Only in this way can we give full play to the advantages of PPP and realize its expected economic value. Secondly, with the world economy threatened by COVID-19, ensuring the stable investment and supply of infrastructure is a major way to counter economic downturn and stabilize social operation. Against the backdrop of China's fundamental vision of becoming a country with strong transportation network, improving the quality and efficiency of transportation infrastructure has become more of a priority. In this situation, PPP becomes an inevitable choice, which has made outstanding contributions in boosting investment and economic performance despite COVID-19. Consequently, there is still an extreme necessity to promote high-quality PPP investment to form sustaining economic driving force for long-term sustainable development, especially in the global context of low-carbon economic development.

5.3. Limitations of the Study

This study still has some potential limitations. Firstly, this paper takes China's reality as the context to explore the impact of transportation PPP investment on the low-carbon economy, but how effective it is in other countries remains unstudied. Even so, conclusions still have certain referential significance for other countries to develop transportation PPP investment, especially for developing countries. Secondly, limited by data availability, the impact of failed projects has not been verified; thus, we cannot highlight a contrast with successful projects. Additionally, due to the paper's space constraints, further discussions on the heterogeneity of regions and project characteristics of transportation PPP investment in different subsectors have not been carried out deeply. All these are worthy of future research attention. In the next step of the study, this paper will take countries along the Belt and Road as the research object to further discuss the impact of transportation PPP investment on the low-carbon economy of these countries, so as to extend the findings of this study.

6. Conclusions

The results show that: (1) transportation PPP investment markedly promotes the low-carbon economic development of China from 2006 to 2018, which is manifested as the dual improvement effects of benefits and efficiency of the low-carbon economy. (2) Transportation PPP investment can not only promote local low-carbon economic development,

but also have a positive spatial spillover effect on neighboring cities. (3) There is a chain relationship between transportation PPP investment and the low-carbon economy through the industrial structure. Namely, transportation PPP investment can promote low-carbon economic development by promoting the upgrading of the industrial structure, which is further manifest as the spatial conduction mechanism. (4) The impacts of transportation PPP investment in different subsectors are significantly heterogeneous. Road PPP has the strongest promotion effects on China's low-carbon economy. Railway PPP contributes more to the regional low-carbon economy. Subway PPP can improve low-carbon economic benefits rather than efficiency. (5) Transportation PPP investment has a continuous and stable effect on promoting the low-carbon economy in China, which highlights the connotation of economic sustainability in the PPP mode. (6) At the micro-project level, the participation of state-owned enterprises and listed companies has a significant positive impact, and state-owned capital is more effective in PPP projects of relatively large scales. While a longer franchise period and a larger proportion of government shareholding in PPP project companies will reduce the contribution of transportation PPP investment to the low-carbon economy on the whole.

In conclusion, it is absolutely necessary to recognize the indispensable role of transportation PPP investment in low-carbon economic development. In the process of realizing the low-carbon economy, it is critical to make full use of high-quality transportation PPP investment to achieve the coordinated and sustainable development of carbon reduction and economic growth under more effective institutional arrangements. Furthermore, led by the example of the Belt and Road Initiative proposed by China, taking the connection of transportation infrastructure as a bridge and linking it to promote the sound development of a low-carbon economy around the world is possible. In addition, with sustainable regional development as the goal, we must foster a new pattern of coordinated low-carbon development among cities through transportation PPP investment. In the top-level design of PPP projects, different types of social capital, including state-owned enterprises and listed companies, should be encouraged to participate and bring in their diversified advantages to empower the performance of projects.

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Article

Public–Private Partnership Infrastructure Investment and Sustainable Economic Development: An Empirical Study Based on Efficiency Evaluation and Spatial Spillover in China

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Abstract: Public–private partnership (PPP), an innovative mode of infrastructure investment, has been widely applied in China and has become an essential policy tool with which to promote sustainable economic development. In order to comprehensively evaluate the economic consequences, using 31 provinces in China from 2003 to 2018 as samples, first, stochastic frontier analysis was performed to measure the input–output efficiency of infrastructure investment to evaluate the economic sustainability and efficiency of PPP compared to single government-led investment mode. Next, the overall economic growth effect of PPP was verified. Further, from the perspective of sustainable development of regional economies, the double-fixed effect spatial Durbin model was adopted to empirically test the spatial spillover effect of PPP and clarify its industrial heterogeneity. The results show the following. (1) The average input–output efficiency of infrastructure is 0.449, revealing a distribution law of decreasing from east to west and remarkable regional variation. However, a good trend of improvement emerged, reflecting the economic sustainability of infrastructure investment, and PPP has played a positive role in promoting it. (2) PPP has significant and positive economic growth and spatial spillover effects, which can promote regional economic integration, embodying its economic sustainability function. (3) The economic impact of PPP has significant industrial heterogeneity. Transportation PPP can bring greater economic benefits, confirming the vital position of transportation infrastructure in the sustainable development of regional economies. Energy and water PPP have positive externalities. All of this provides powerful and reliable proof of the realization of sustainable economic development under the regional virtuous circle driven by infrastructure investment through PPP.

Keywords: public–private partnership; infrastructure investment; sustainable development; input–output efficiency; spatial spillover; heterogeneity; economic disparity

1. Introduction

Interconnected infrastructure is an essential foundation for sustainable economic development. As China's economy enters the new normal, the contradiction between the continuously growing demand for public goods represented by infrastructure and the insufficient supply efficiency and quality of single government-led investment mode under downward economic pressure and fiscal constraints has profoundly changed the supply and investment mode of infrastructure. PPP has become the most important means of investing in infrastructure. By June 2021, China's total PPP investment in infrastructure reached 15.59 trillion yuan, the largest share of which is transportation, accounting for 33.42%, or 5.21 trillion yuan. Moreover, given China's unique national conditions, unbalanced and inadequate development among regions remains a crucial long-term problem that restricts high-quality economic development. In this context, the Chinese government anticipates that PPP will promote sustainable economic development and create a new mechanism for coordinated regional development.

Compared to single government-led investment mode, can PPP bring economic sustainability and efficiency? Does PPP have economic growth and spatial spillover effects? Are there differences in the impacts of different industries? Existing studies have made extensive evaluations on the economic consequences of PPP, but most of them are theoretical and case studies based on questionnaire surveys and other qualitative methods, while only a few take China's data as a sample for empirical analysis on a macro scale. Some studies have directly investigated the impact of PPP on GDP and the possible influencing factors between them. Their results show that PPP has a significant positive effect on promoting economic growth [1,2] by enhancing the effectiveness of the implementation of fiscal and monetary policies, improving the mismatch of resources, and increasing total factor productivity [3,4]. Some studies in other countries have also proven that PPP is effective for economic development [5,6]. In addition, some studies have evaluated the economic impact of PPP from the perspective of infrastructure efficiency, showing a significant positive correlation between PPP and infrastructure efficiency in countries along the Belt and Road [7,8], while PPP was not shown to significantly improve the output efficiency of infrastructure in China when 245 cities from 2002 to 2015 were taken as a sample with the use of the multiperiod DID method [9].

In terms of the spatial spillover effect, most related studies have focused more on evaluating the impact of single government, social capital, or sector-specific investment. It was found that government investment can generate economic growth and spatial spillover effects [10], and it is a chain relationship in which private parties can improve economic performance through technological innovation [11], which can generate a positive spatial spillover effect [12], but may also become an obstacle to economic development [13]. Only one cross-regional study creatively considered the spatial effect of PPP and showed that it has a direct promoting effect and an indirect spillover effect on economic growth [14], but the sample for that study was the Belt and Road countries.

Based on the above, there are three scientific gaps worth filling. (1) Few studies have used rigorous econometric techniques to evaluate the economic consequences of PPP, and the dimensions of existing empirical studies are relatively narrow, so a comprehensive study evaluating the economic impact of PPP from the perspective of sustainable development is lacking. (2) In most studies, PPP is regarded as a policy impact that is treated as a dummy variable, so the accuracy of results needs to be verified and improved. Moreover, there is no consensus on the economic consequences of PPP, which needs further research and analysis. (3) The spatial spillover effect of PPP on regional economic development and the industrial heterogeneity of PPP are not widely discussed. It is worth enriching and extending this topic. All of these provide scope for this paper based on sample data with Chinese characteristics.

Accordingly, this paper conducts a comprehensive empirical examination of the impact of PPP on China's sustainable economic development from the dual dimensions of efficiency evaluation and spatial spillover based on the perspective of sustainability, and further explores the industrial heterogeneity of PPP to get more detailed conclusions. The main contributions and added value are as follows: (1) the input–output efficiency of infrastructure is scientifically evaluated and the implementation effect of PPP in China is verified, which has important practical significance for further improvement and promotion of PPP; (2) the spatial effect mechanism and effect of PPP are clarified, which bridges the gaps in the existing research and represents a useful attempt to approach this issue from the spatial economic perspective; and (3) the industrial heterogeneity of PPP in economic development is explored, which provides a reference basis for the development of PPP in different fields.

The paper is organized as follows: the theoretical analysis and research hypothesis are presented in Section 2 in order to establish the theoretical basis and empirical logic framework. The data, variables, and model used in this paper are included in Section 3. Section 4 presents the empirical analysis, which is the key content of this paper, including the analyses of infrastructure input–output efficiency, economic growth and spatial

spillover effects, and industry heterogeneity of PPP. Section 5 discusses and explains the results from the perspective of previous studies and working hypotheses. The last section presents the conclusion and suggestions.

2. Theoretical Analysis and Research Hypothesis

2.1. Impact of PPP on Input–Output Efficiency of Infrastructure

In economics, efficiency is the ideal maximum possible output with the same input or the ideal minimum possible input with the same output. The input–output efficiency of infrastructure evaluates the configuration state between infrastructure input and economic output within the concept of sustainable economic development. In the past, infrastructure investment was carried out by local Chinese governments, which led to monopolies. It was not until 2014 that PPP was applied on a large scale and gradually replaced single government-led investment, and the marketization of infrastructure investment gradually emerged.

According to public goods theory, in the new political economy, public good related to the national economy cannot be completely provided by a profit-maximizing market, but needs government intervention. The theory of welfare economics further points out that the government's powerful macro control should be limited to taxes and subsidies, and the task of optimizing the allocation of market resources should be left to private parties through market competition. Against the background of the Chinese system, PPP, as a mixed semi-organizational and semi-market economic form, can improve the efficiency and optimize the structure of resource allocation in infrastructure investment and promote the input–output efficiency of infrastructure through a synergistic effect.

On the one hand, the core mechanism of PPP is to introduce market mechanisms to infrastructure provision, letting the market participate in the allocation and management of public resources, which can effectively avoid the drawback of the “grabbing hands” of local governments caused by long-term administrative monopolies [15]; this is conducive to eliminating the inefficiency of the pattern of government-only status [16]. On the other hand, under the organic combination of the dual efficiencies of government and market, the competitive mechanism will further guide local governments' financial resources to other areas and weak links of people's livelihoods, and build a mechanism for more favorable cooperation between governments and private parties. This can promote the structural adjustment of resource allocation in government financial expenditure and the participation of private parties, in order to form a long-term sustainable supply mode that pursues infrastructure quality and efficiency [17]. Furthermore, the synergy effect of PPP is due to the complementary advantages of governments and private parties [18]. Local governments have macroscopic control and risk resistance ability and can implement powerful policy guidance; the added value of private parties, such as knowledge, skills, management experience, and innovation, becomes more productive with cooperation. PPP can also encourage professional institutions to participate in infrastructure construction, operation, and management, thus forming a “1 + 1 + 1 > 3” performance improvement mechanism of governments, private parties, and professional institutions [19]. Therefore, compared to the government-led single investment mode, PPP more reflects the win–win of economic and social benefits based on the synergistic effect.

Accordingly, the first research hypothesis is proposed.

Hypothesis 1A. *PPP is positively correlated with the input–output efficiency of infrastructure.*

Hypothesis 1B. *Compared with the single government-led investment mode, PPP has a more significant promoting effect on the input–output efficiency of infrastructure.*

2.2. Overall Economic Growth Effect of PPP

This paper analyzes the economic growth effect of PPP from the perspective of institutional innovation. According to the theory of institutional economics, effective institutional design is the key to ensuring and improving economic growth. Institutional innovation refers to reforming the existing system by key players in order to obtain specific benefits [20], which includes two forms, induced and mandatory. Induced institutional innovation achieves Pareto optimality through gradual accumulation of changes under the premise of compatible interests of various stakeholders. The effectiveness of institutional innovation is reflected in the coordination of interest distribution relationships among stakeholders, enhancing the interests of some stakeholders without harming others, so as to reach a consensus on reform, which can bring the bonus effect of institutional innovation to promote economic growth [21].

The essence of PPP is that it is an institutional design and innovation that gives full play to the respective endowment advantages of governments and private parties to carry out mutual long-term cooperation for the efficient supply of infrastructure and services. The understanding of PPP should be promoted to the level of institutional mechanisms, with the improvement of institutional efficiency as the core. The reform process of PPP in China is consistent with the logical process of institutional economics. With the transition of China's economy, the institutional arrangement of administrative monopolies in which local governments are the sole agents carrying out infrastructure investment, construction, and operation is difficult to sustain. Various drawbacks can be found, such as shortages of fiscal funds, insufficient supply capacity, and inefficient resource distribution. At this point, PPP, as an induced institutional innovation of "gradualism" initiated by the government, not only enables better realization of the government's public service functions, but also provides opportunities for private parties to gain economic benefits and fulfill social responsibilities, and bring more quality and inexpensive products and services to the public by giving full play to the endowment advantages of all parties through PPP's specialized cooperation mechanism. Thus, the Pareto optimality of the "triple win" of governments, private parties, and people's livelihoods can be achieved [22]. Moreover, the cost of induced institutional innovation is relatively low, the social unrest is relatively small, and the intervention of local governments can make it progress more smoothly [23].

PPP gives adequate consideration to economic efficiency and social equity, which strongly conforms to the core connotation of institutional innovation. China's development experience has proven that PPP is key to deepening supply-side reform, introducing mixed ownership to SOEs, and innovating the mode of infrastructure investment. Therefore, it can be assumed that PPP, as an effective institutional innovation, has the overall economic benefit of promoting sustainable economic development. In addition to giving play to the "invisible hands" of the institution, PPP as an investment has a natural capital accumulation effect, thus can promote economic development. According to investment multiplier theory, PPP can drive the investment of the whole society, thus stimulating employment and consumption, and can improve the scale and quality of infrastructure provision to lay a solid foundation for industrial agglomeration.

Accordingly, the second research hypothesis is proposed.

Hypothesis 2. *PPP is positively correlated with GDP, manifested as an economic growth effect.*

2.3. Spatial Economic Spillover Effect and Industrial Heterogeneity of PPP

The mechanism of PPP that can exert a spatial spillover effect lies in the functional attributes of infrastructure and the spatial autocorrelation of economic development.

First, infrastructure is networked. As an important carrier of economic connections between regions, the connectivity of infrastructure can realize the spatial flow of production factors, break the market segmentation caused by the administrative division or spatial distance of regions, and connect different regions as a whole. In particular, transportation infrastructure creates an indispensable basis for guiding the distribution of

productivity and the spatial distribution of the population, and also lays a solid foundation for improving the efficiency and competitiveness of regional economies. China attaches great importance to the networked economic advantages of transportation infrastructure, and has put forward the Belt and Road initiative and the strategy of building a country with a strong transportation network, which has become the “Chinese experience” that is valued worldwide.

Second, infrastructure has externalities, arising from the function of public goods. This means the social benefits of infrastructure often exceed its economic benefits, which means that infrastructure is not intended to make a profit, but to provide the necessary external conditions for the microeconomy and the necessary complementary goods for private capital, and to ensure the normal functioning of social and economic activities in a country or region. Marshall, in his book *Principles of Economics*, theorized about the extensive impact of infrastructure on other production units and summarized that the externalities of public goods have a spillover effect on economic growth. Pigou further distinguished and developed the theory of externality and spillover effects. The external benefit that infrastructure brings to other production units is called external economy or positive spillover, while the external effect that brings losses is called external diseconomy or negative spillover. In addition, the externalities of different types of infrastructure are heterogeneous. Transportation infrastructure not only has a direct impact on economic growth, but also has stronger externality, which has positive synergistic and spatial spillover effects [24,25]. Energy infrastructure is better reflected as an external economy [26], while the new energy has a negative external economic impact in China’s developing areas [27].

Third, the spatial dependence of economic development is one of the prerequisites for the spatial spillover effect [28]. Spatial dependence refers to the relationships among things or social phenomena, depending on and even restricting each other in the spatial dimension. The existence of spatial dependence indicates that the occurrence and development of things or social phenomena are always influenced by other units. Economic development obviously has such spatial dependence. The economic development of different regions is not only determined by their production capacity, but also affected by the development situation of other regions, which is related to the flow of production factors and the links of communication, distribution, and consumption. It is precisely because of the spatial dependence of economic development that improving the infrastructure in one region can promote the development of that region and also have an impact on the development of other regions [29].

Accordingly, the third research hypothesis is proposed.

Hypothesis 3A. *PPP has a positive spatial spillover effect that can promote local economic development and the economic development of neighboring areas.*

Hypothesis 3B. *The spatial spillover effect of PPP varies by industry, and transportation PPP has a stronger economic effect and spatial spillover.*

3. Data, Variables, and Model

3.1. Data Sources

In the evaluation of the infrastructure input–output efficiency, the GDP of 31 provinces was selected as output, total infrastructure investment from various industries (transportation, energy, water, etc.) and various entities (government, enterprise, private) as capital input, and number of people employed in the infrastructure sector as labor input.

In empirically examining the impact of PPP on sustainable economic development, we used data from 31 provinces in China from 2003 to 2018 as panel samples. Data of PPP infrastructure investment come from the World Bank Private Participation in Infrastructure Database and the China Public–Private Partnerships Center. In order to ensure the reliability and validity of the study, this paper kept the PPP data from the executed infrastructure investment projects and excluded the data from discontinued

or abolished projects. Except for the telecom industry, due to its highly monopolistic nature and smaller sample size, PPP data of the transportation, energy, and water sectors were selected to analyze industry heterogeneity. The economic development data of the 31 provinces came from the China Statistical Yearbook and National Economy and Social Development Statistics Bulletin from 2004 to 2019, and the marketization index came from a research report released by the China National Economic Research Institute.

3.2. Variable Descriptions

The total infrastructure investment and number of people employed in the infrastructure sector were taken as input variables, and GDP was taken as an output variable to measure the input–output efficiency of infrastructure. In the regression analysis, GDP and infrastructure input–output efficiency were selected as the explained variables. PPP infrastructure investment was taken as the explanatory variable. Referring to relevant studies [30–32], the fiscal self-sufficiency rate, fiscal burden rate, foreign trade dependence degree, marketization index, level of human capital, and population size were taken as control variables. The fiscal self-sufficiency rate is the ratio of fiscal revenue to fiscal expenditure, which represents the degree of local fiscal self-reliance. China uses a revenue-sharing system between the central government and local governments, that is, the central government will balance the economic development of different regions through the fiscal transfer system. Therefore, the higher the level of local fiscal self-sufficiency, the less dependence on the central government and the stronger the local economic power. The fiscal burden rate is the ratio of fiscal revenue to GDP, which comprehensively reflects the relationship between local governments and other microeconomic entities in occupying and dominating social resources, and also represents the government’s capacity for macroeconomic control and the extent to which it affects the allocation of social resources. Consequently, it is necessary to keep the fiscal burden at a reasonable level. According to general practice, the level of human capital is measured by the weighted average of years of schooling for people of different ages. The meanings and descriptive statistics of variables are shown in Tables 1 and 2.

Table 1. Meaning and calculation of variables.

Variable	Meaning	Calculation
GDP	Gross domestic product	Take logarithm
CI	Infrastructure capital input	Take logarithm
LI	Infrastructure labor input	Take logarithm
IE	Infrastructure input–output efficiency	Use SFA method in Section 4.1
PPP	PPP infrastructure investment	Take logarithm
GI	Government infrastructure investment	Take logarithm
SU	Fiscal self-sufficiency rate	Divide revenue by expenditure
BU	Fiscal burden rate	Divide revenue by GDP
OP	Foreign trade dependence degree	Divide total foreign trade by GDP
MI	Marketization index	Taken from research report
CP	Human capital level	Use weighted average of schooling years of people at different ages
PO	Population size	Divide population by land area

Table 2. Descriptive statistics of variables.

Variable	Observations	Mean	Sd	Min	Max
GDP	496	9.135	1.164	5.218	11.485
CI	496	8.556	1.289	4.773	10.941
LI	496	7.509	0.899	4.889	8.819
IE	496	0.449	0.222	0.111	0.977
PPP	496	3.420	2.619	0	9.403
GI	496	8.457	1.468	0	10.930
SU	496	0.498	0.203	0.056	0.951
BU	496	0.098	0.033	0.044	0.227
OP	496	0.045	0.055	0.003	0.259
MI	496	6.255	2.068	−0.230	11.710
CP	496	10.685	1.450	4.524	15.184
PO	496	5.280	1.480	0.788	8.250

3.3. Model Specification

3.3.1. Model for Measuring Input–Output Efficiency of Infrastructure

Production frontier analysis is a mainstream method of efficiency measurement that includes stochastic frontier analysis (SFA) and data envelope analysis (DEA). Both of them construct the possible production frontier and measure the distance between the individual output and the frontier in order to figure out the individual efficiency. Compared with DEA, SFA is a parameter estimation method based on the production function, which has more stringent requirements for model and data accuracy. In addition, SFA considers the impact of random factors on output and can flexibly choose the production function form according to the nature of the research object, in order to make the evaluation more accurate and targeted [33–35]. Therefore, this study used the SFA method to measure the input–output efficiency of infrastructure.

Given that infrastructure investment is a multi-objective, multivariate, and nonlinear input–output system [36], compared to the Cobb–Douglas production function, the assumptions of the trans-log production function are more in line with economic reality. Based on a time-varying model [37], the model is set up as follows:

$$\ln Y_{it} = \beta_0 + \beta_1 \ln K_{it} + \beta_2 \ln L_{it} + \beta_3 t + \frac{1}{2} \beta_4 (\ln K_{it})^2 + \frac{1}{2} \beta_5 (\ln L_{it})^2 + \frac{1}{2} \beta_6 t^2 + \beta_7 \ln K_{it} \ln L_{it} + \beta_8 t \ln K_{it} + \beta_9 t \ln L_{it} + v_{it} - u_{it} \quad (1)$$

$$u_{it} = e^{-\eta(t-T)} u_i \quad (2)$$

In Formula (1), Y_{it} is output, K_{it} is capital input, L_{it} is labor input, β_1 is capital output elasticity, and β_2 is labor output elasticity; $v_{it} - u_{it}$ is a composite error term.

In Formula (2), η is a time-varying coefficient and $\eta > 0$ indicates improved efficiency over time.

The input–output efficiency of infrastructure is defined as:

$$IE_{it} = e^{-u_{it}} \quad (3)$$

In Formula (3), when $u = 0$ and $IE = 1$, the individual output is equal to the maximum output and there is a state of efficiency. When $u > 0$ and $0 < IE < 1$, it indicates that the individual output is less than the maximum output and there is a state of inefficiency.

3.3.2. Model for Examining the Impact of PPP on Sustainable Economic Development

This paper first sets up model (4) to investigate the impact of PPP on infrastructure input–output efficiency, in order to identify the economic efficiency in terms of sustainability. In order to compare the impact difference between PPP and single government-led investment, the comparison model (5) was also constructed.

$$IE_{it} = \alpha_0 + \alpha_1 PPP_{it} + \alpha_2 SU_{it} + \alpha_3 BU_{it} + \alpha_4 OP_{it} + \alpha_5 MI_{it} + \alpha_6 CP_{it} + \alpha_7 PO_{it} + \gamma_1 + \delta_t + u_{it} \quad (4)$$

$$IE_{it} = \alpha_0 + \alpha_1 GI_{it} + \alpha_2 SU_{it} + \alpha_3 BU_{it} + \alpha_4 OP_{it} + \alpha_5 MI_{it} + \alpha_6 CP_{it} + \alpha_7 PO_{it} + \gamma_i + \delta_t + u_{it} \quad (5)$$

In Formulas (4) and (5), IE is the input–output efficiency of infrastructure; GI and PPP, respectively, represent single government and PPP infrastructure investment (these coefficients measure the net effect of the two modes on infrastructure input–output efficiency, which is the focus of the comparison); i represents the province and t represents the year; and γ_i , δ_t represent the fixed effect of province and year, respectively.

Then, the economic growth effect of PPP is verified to provide the necessary premise for the research of the spatial spillover effect of PPP. Without considering the spatial effect, the traditional empirical model of PPP and GDP is constructed as follows:

$$GDP_{it} = \alpha_0 + \alpha_1 PPP_{it} + \alpha_2 SU_{it} + \alpha_3 BU_{it} + \alpha_4 OP_{it} + \alpha_5 MI_{it} + \alpha_6 CP_{it} + \alpha_7 PO_{it} + \gamma_i + \delta_t + u_{it} \quad (6)$$

The spatial economic effect of PPP is not considered in Formula (6), which may lead to imperfect model specification and bias in the parameter estimation. To overcome this defect, Griffith proposed introducing the spatial weight matrix into the traditional model and extended the research perspective to the spatial effect by considering the potential spatial interdependence among variables [38].

The commonly used spatial weight matrix includes adjacency, distance, and economic matrices, which respectively represent geographic adjacency, geographic distance, and differences in the level of economic development between regions. Given the function and attributes of the infrastructure, the distance matrix more appropriately reflects the spatial relationship between PPP and regional economy. The elements of the distance matrix are calculated in this paper as the reciprocal of the square of the geographic longitude and latitude distances between two regions. On the basis of model (6), the distance matrix is added to construct the spatial Durbin model.

$$GDP_{it} = \rho \sum_{j=1}^N W_{ij} * GDP_{jt} + \alpha_1 PPP_{it} + \sum \alpha_k Control_{it} + \beta_1 \sum_{j=1}^N W_{ij} * PPP_{jt} + \sum \beta_k \sum_{j=1}^N W_{ij} * Control_{jt} + \gamma_i + \delta_t + u_{it} \quad (7)$$

In Formula (7), ρ is the spatial lag coefficient, reflecting the spatial dependence between regional economies; Control represents the set of control variables; W represents the $N * N$ dimensional spatial distance matrix; α and β measure the impact of each factor on the economic development of the local and neighboring areas, respectively; and β_1 represents the spatial spillover effect of PPP on economic development.

4. Empirical Analysis

4.1. Measurement and Analysis of Input–Output Efficiency of Infrastructure

Models (1)–(3) were used to measure the input–output efficiency of infrastructure in China's 31 provinces from 2003 to 2018. Model parameter estimates are shown in Table 3. The efficiency calculation results are shown in Table 4.

The likelihood ratio is significant at a level of 1%, indicating that the model has good statistical properties, and $\gamma = 0.9301$, which is close to 1, indicating that the error term has a very obvious composite structure. Thus, it is necessary to use SFA instead of DEA's simple linear programming to analyze economic data over as long as 16 years, which again confirms the reliability of the model. Furthermore, $\eta = 0.0169 > 0$, indicating that the input–output efficiency of infrastructure improves continuously, reflecting an obvious improvement trend.

Table 3. Model parameter estimates of SFA.

Parameter	Coefficient	t-Ratio
β_0	0.933	0.93
β_1	0.396 **	2.02
β_2	1.211 ***	3.91
β_3	0.045	1.26
β_4	0.031	0.76
β_5	−0.023	−0.41
β_6	−0.011 ***	−4.89
β_7	−0.074 **	−2.11
β_8	0.008	0.97
β_9	0.007	0.93
σ^2	0.094 ***	5.57
γ	0.930 ***	100.76
u	0.592 ***	4.24
η	0.017 ***	3.62
Log likelihood function	395.85 ***	
Likelihood ratio	1314.16 ***	

Note: ***, **, * indicate statistical significance of 99, 95, and 90%, respectively.

Table 4. Infrastructure input–output efficiency of provinces from 2003 to 2018.

Province/Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Average
Beijing	0.717	0.721	0.725	0.729	0.733	0.737	0.740	0.744	0.748	0.751	0.755	0.759	0.762	0.766	0.769	0.772	0.746
Tianjin	0.531	0.536	0.542	0.548	0.553	0.559	0.564	0.570	0.575	0.580	0.586	0.591	0.596	0.601	0.607	0.612	0.572
Hebei	0.468	0.474	0.479	0.485	0.491	0.497	0.503	0.509	0.515	0.520	0.526	0.532	0.538	0.543	0.549	0.554	0.511
Shanxi	0.313	0.319	0.325	0.331	0.338	0.344	0.350	0.356	0.363	0.369	0.375	0.381	0.387	0.394	0.400	0.406	0.359
Inner Mongolia	0.398	0.404	0.410	0.417	0.423	0.429	0.435	0.441	0.447	0.453	0.459	0.465	0.471	0.477	0.483	0.489	0.444
Liaoning	0.522	0.528	0.534	0.539	0.545	0.551	0.556	0.562	0.567	0.572	0.578	0.583	0.588	0.594	0.599	0.604	0.564
Jilin	0.332	0.338	0.344	0.350	0.357	0.363	0.369	0.375	0.382	0.388	0.394	0.400	0.406	0.413	0.419	0.425	0.378
Heilongjiang	0.369	0.375	0.382	0.388	0.394	0.400	0.406	0.413	0.419	0.425	0.431	0.437	0.443	0.449	0.455	0.462	0.416
Shanghai	0.877	0.879	0.881	0.883	0.885	0.886	0.888	0.890	0.892	0.893	0.895	0.897	0.898	0.900	0.902	0.903	0.890
Jiangsu	0.891	0.893	0.894	0.896	0.898	0.899	0.901	0.902	0.904	0.905	0.907	0.908	0.910	0.911	0.913	0.914	0.903
Zhejiang	0.704	0.708	0.712	0.716	0.720	0.724	0.728	0.732	0.736	0.740	0.744	0.747	0.751	0.754	0.758	0.762	0.734
Anhui	0.281	0.287	0.293	0.299	0.305	0.311	0.317	0.324	0.330	0.336	0.342	0.348	0.355	0.361	0.367	0.373	0.327
Fujian	0.469	0.475	0.481	0.487	0.493	0.499	0.505	0.511	0.516	0.522	0.528	0.534	0.539	0.545	0.550	0.556	0.513
Jiangxi	0.269	0.275	0.281	0.287	0.293	0.299	0.305	0.312	0.318	0.324	0.330	0.336	0.342	0.349	0.355	0.361	0.315
Shandong	0.748	0.752	0.756	0.759	0.763	0.766	0.770	0.773	0.776	0.780	0.783	0.786	0.789	0.792	0.795	0.798	0.774
Henan	0.433	0.439	0.445	0.451	0.457	0.463	0.469	0.475	0.481	0.487	0.493	0.499	0.505	0.511	0.517	0.522	0.478
Hubei	0.390	0.397	0.403	0.409	0.415	0.421	0.427	0.434	0.440	0.446	0.452	0.458	0.464	0.470	0.476	0.482	0.436
Hunan	0.368	0.374	0.380	0.386	0.392	0.399	0.405	0.411	0.417	0.423	0.430	0.436	0.442	0.448	0.454	0.460	0.414
Guangdong	0.971	0.971	0.972	0.972	0.972	0.973	0.973	0.974	0.974	0.975	0.975	0.975	0.976	0.976	0.977	0.977	0.974
Guangxi	0.258	0.264	0.270	0.276	0.282	0.288	0.294	0.300	0.307	0.313	0.319	0.325	0.331	0.337	0.344	0.350	0.304
Hainan	0.194	0.199	0.205	0.210	0.216	0.222	0.227	0.233	0.239	0.245	0.250	0.256	0.262	0.268	0.274	0.280	0.236
Chongqing	0.287	0.293	0.299	0.305	0.312	0.318	0.324	0.330	0.336	0.342	0.349	0.355	0.361	0.367	0.374	0.380	0.333
Sichuan	0.367	0.373	0.379	0.385	0.391	0.398	0.404	0.410	0.416	0.422	0.429	0.435	0.441	0.447	0.453	0.459	0.413
Guizhou	0.168	0.173	0.178	0.183	0.188	0.194	0.199	0.205	0.210	0.216	0.221	0.227	0.233	0.238	0.244	0.250	0.208
Yunnan	0.215	0.221	0.226	0.232	0.238	0.244	0.249	0.255	0.261	0.267	0.273	0.279	0.285	0.291	0.297	0.303	0.259
Tibet	0.111	0.115	0.119	0.124	0.128	0.132	0.137	0.142	0.146	0.151	0.156	0.161	0.166	0.171	0.176	0.181	0.145
Shaanxi	0.302	0.308	0.314	0.321	0.327	0.333	0.339	0.345	0.351	0.358	0.364	0.370	0.376	0.383	0.389	0.395	0.348
Gansu	0.165	0.170	0.175	0.180	0.185	0.190	0.196	0.201	0.207	0.212	0.218	0.223	0.229	0.235	0.241	0.246	0.205
Qinghai	0.156	0.161	0.166	0.171	0.176	0.181	0.187	0.192	0.197	0.203	0.208	0.214	0.219	0.225	0.231	0.236	0.195
Ningxia	0.172	0.177	0.182	0.187	0.193	0.198	0.203	0.209	0.214	0.220	0.226	0.231	0.237	0.243	0.249	0.255	0.212
Xinjiang	0.284	0.290	0.297	0.303	0.309	0.315	0.321	0.327	0.333	0.340	0.346	0.352	0.358	0.364	0.371	0.377	0.330

Note: Provinces are ranked according to standard order of China Statistical Yearbook; results were processed by Front 4.1.

The overall average input–output efficiency of infrastructure is 0.449, far below 1, which is a state of inefficiency. Despite this, from 2003 to 2018, the input–output efficiency in each province continuously improved year by year, indicating a good trend of sustainable improvement. The input–output efficiency has obvious differences in different provinces. The highest is 0.974, on average, in Guangdong, the most economically developed province, with its GDP ranking first for 30 consecutive years among all the provinces, and the lowest

is 0.145 in Tibet, which is economically backward, with its GDP ranking last. It can be assumed that the input–output efficiency of infrastructure is closely related to the level of economic development.

To further investigate the regional differences in input–output efficiency, the provinces were grouped into four economic regions according to the classification criteria on socioeconomic development released by the Chinese government. The results are shown in Table 5.

Table 5. Input–output efficiency of infrastructure in four economic regions.

Region	Provinces	Average
East	Guangdong, Jiangsu, Shanghai, Shandong, Beijing, Zhejiang, Tianjin, Fujian, Hebei, Hainan	0.685
Northeast	Liaoning, Heilongjiang, Jilin	0.453
Middle	Henan, Hubei, Hunan, Shanxi, Anhui, Jiangxi	0.388
West	Inner Mongolia, Sichuan, Shaanxi, Chongqing, Xinjiang, Guangxi, Yunnan, Ningxia, Guizhou, Gansu, Qinghai, Tibet	0.283

As can be seen intuitively from Table 5, the input–output efficiency of infrastructure in different regions has obvious heterogeneity and sequencing. It generally presents a distribution trend and characteristics of decrease from east to west. The average efficiency of the eastern region, with the highest economic development, is 0.685 and that of the western region, with the lowest level of economic development, is 0.283. This again shows that the input–output efficiency of infrastructure is related to the level of economic development. These results indicate remarkable discrepancies and imbalance in regional development, which is highly consistent with China’s national conditions and economic reality.

4.2. Impact of PPP on Input–Output Efficiency of Infrastructure

Models (4) and (5) were used to test the impact of PPP and single government investment, respectively, on the input–output efficiency of infrastructure. The results are shown in Tables 6 and 7.

Regardless of whether control variables are added, both PPP and single government investment are always positively correlated with the input–output efficiency of infrastructure, highlighting the economic sustainability of infrastructure investment. Hypothesis 1A can be confirmed. Compared to single government investment, PPP has a more significant effect on the input–output efficiency of infrastructure and its coefficient is larger, indicating its inherent advantage in leveraging greater investment efficiency with less capital. Hypothesis 1B can be confirmed. This also confirms that the core significance of PPP is not only to reduce the government’s financial burden, but also to improve the economic efficiency of public goods by introducing social capital and its inherent sense of competition, concept of market value investment, and market risk consciousness.

Table 6. Impact of PPP on input–output efficiency of infrastructure.

Variables	Explained Variable: IE						
	1	2	3	4	5	6	7
PPP	0.022 *** (5.66)	0.005 *** (2.88)	0.003 ** (2.35)	0.003 ** (2.32)	0.003 ** (2.29)	0.003 ** (2.29)	0.003 ** (2.33)
SU		0.963 *** (41.69)	1.066 *** (42.06)	0.713 *** (23.74)	0.779 *** (14.51)	0.775 *** (14.17)	0.804 *** (14.81)
BU			−1.424 *** (−7.90)	−2.645 *** (−16.13)	−2.764 *** (−15.17)	−2.777 *** (−15.03)	−2.579 *** (−13.70)
OP				1.969 *** (16.05)	1.991 *** (16.14)	1.993 *** (16.13)	1.812 *** (13.97)
MI					−0.007 (−1.49)	−0.007 (−1.54)	0.004 (0.72)
CP						0.017 (0.45)	0.049 (1.30)
PO							−0.019 *** (−4.03)
Year	Control	Control	Control	Control	Control	Control	Control
Province	Control	Control	Control	Control	Control	Control	Control
R ²	26.34%	79.78%	82.12%	88.40%	88.45%	88.46%	88.84%
N	496	496	496	496	496	496	496

Note: Values in parentheses are t statistics. ***, **, * indicate statistical significance of 99, 95, and 90%, respectively. Results were processed by Stata 14.0.

Table 7. Impact of single government investment on input–output efficiency of infrastructure.

Variables	Explained Variable: IE						
	1	2	3	4	5	6	7
GI	0.002 *** (3.16)	0.002 ** (2.46)	0.002** (2.31)	0.001 ** (2.27)	0.001 ** (2.02)	0.001 * (1.93)	0.001 * (1.78)
SU		−0.001 (−0.04)	0.009 (0.82)	−0.002 (−0.20)	−0.004 (−0.42)	−0.005 (−0.57)	0.001 (0.10)
BU			−0.070 * (−1.81)	−0.033 (−1.00)	−0.014 (−0.41)	−0.001 (−0.02)	0.022 (0.64)
OP				0.285 *** (12.99)	0.288 *** (13.24)	0.294 *** (13.46)	0.254 *** (10.73)
MI					0.002 *** (3.09)	0.002 ** (2.54)	0.002 *** (2.59)
CP						0.016 ** (2.20)	0.016 ** (2.15)
PO							−0.030 *** (−4.05)
Year	Control	Control	Control	Control	Control	Control	Control
Province	Control	Control	Control	Control	Control	Control	Control
R ²	92.36%	92.36%	92.42%	94.50%	94.61%	94.67%	94.86%
N	496	496	496	496	496	496	496

Note: Values in parentheses are t statistics. ***, **, * indicate statistical significance of 99, 95, and 90%, respectively. Results were processed by Stata 14.0.

4.3. Overall Economic Growth Effect of PPP

Model (6) was used to test the overall impact of PPP on economic development. The results are shown in Table 8.

Table 8. Overall economic growth effect of PPP.

Variable	Explained Variable: GDP						
	1	2	3	4	5	6	7
PPP	0.005 ** (2.36)	0.004 ** (2.06)	0.004 ** (2.25)	0.004 ** (2.31)	0.004 ** (2.44)	0.004 ** (2.34)	0.003 * (1.86)
SU		1.239 *** (9.83)	1.474 *** (10.48)	1.485 *** (10.52)	1.443 *** (10.40)	1.470 *** (10.72)	1.530 *** (11.05)
BU			−1.668 *** (−3.59)	−1.708 *** (−3.66)	−1.318 *** (−2.83)	−1.463 *** (−3.17)	−1.262 *** (−2.71)
OP				−0.274 (−0.89)	−0.227 (−0.75)	−0.250 (−0.84)	−0.595 * (−1.82)
MI					0.040 *** (4.33)	0.045 *** (4.83)	0.045 *** (4.85)
CP						0.047 *** (3.64)	0.050 *** (3.86)
PO							−0.261 ** (−2.47)
Year	Control	Control	Control	Control	Control	Control	Control
Province	Control	Control	Control	Control	Control	Control	Control
R ²	97.82%	98.21%	98.26%	98.26%	98.33%	98.38%	98.40%
N	496	496	496	496	496	496	496

Note: Values in parentheses are t statistics. ***, **, * indicate statistical significance of 99, 95, and 90%, respectively. Results were processed by Stata 14.0.

PPP always has a significant and positive correlation with GDP, proving that it has an economic growth effect, which lays the groundwork for the following analysis of the spatial spillover effect. Hypothesis 2 can be confirmed. The coefficient of SU is always significantly positive, while the coefficient of BU is always significantly negative. This suggests that the higher the level of fiscal self-sufficiency, the stronger the ability of local governments to contribute to economic development; in contrast, an excessively high fiscal burden indicates that local governments must concentrate excessive social and financial resources, which is not conducive to stimulating market vitality and thus weakens the sustainability of economic development. The coefficient of CP is significantly positive and the coefficient of PO is significantly negative, indicating that the driving force of economic development is an improved level of human capital rather than population growth. In addition, the marketization level is positively correlated with economic development and the degree of foreign trade dependence is negatively correlated, indicating that economic development is driven by domestic market demand rather than import and export, which conforms with the latest theoretical idea of nurturing a stronger domestic market to establish China's new development pattern.

4.4. Spatial Spillover Effect of PPP

The selection of a spatial econometric model has an important impact on the accuracy of the results. Therefore, the feasibility and reliability of model (7) was tested, as shown in Table 9, proving that the model is appropriate for this study.

It was also necessary to test the spatial dependence of economy between regions as a prerequisite to studying the spatial effect of PPP. Moran's I was used to measure the economic spatial autocorrelation of GDP and IE, as shown in Table 10. The value range of Moran's I is $[-1, 1]$; a value greater than 0 means positive spatial correlation, and a value less than 0 means negative correlation, and the greater the absolute value, the stronger the spatial correlation, showing a more obvious spatial agglomeration effect.

Table 9. Test of spatial econometric model specification.

Test	Statistic	Coefficient	p-Value
Applicability of spatial autoregression model	LM_lag	12.49 ***	0.000
	LM_lag_ro	23.63 ***	0.000
Applicability of spatial error model	LM_err	110.34 ***	0.000
	LM_err_ro	121.48 ***	0.000
Selection of fixed effect types	LR-both_ind	72.43 ***	0.000
	LR-both_time	1662.70 ***	0.000
Comparison of SDM and SAR	Wald_SDM_SAR	26.71 ***	0.000
	LR_SDM_SAR	26.05 ***	0.000
Comparison of SDM and SEM	Wald_SDM_SEM	23.43 ***	0.001
	LR_SDM_SEM	23.64 ***	0.001

Note: ***, **, * indicate statistical significance of 99, 95, and 90%, respectively.

Table 10. Moran's I of GDP and IE.

Year	GDP		IE	
	Moran's I	Z	Moran's I	Z
2003	0.205 ***	2.628	0.019	0.570
2004	0.204 ***	2.619	0.019	0.567
2005	0.195 **	2.532	0.018	0.559
2006	0.191 **	2.487	0.017	0.552
2007	0.189 **	2.458	0.017	0.549
2008	0.188 **	2.453	0.016	0.543
2009	0.195 **	2.534	0.016	0.535
2010	0.193 **	2.529	0.015	0.528
2011	0.191 **	2.506	0.015	0.525
2012	0.188 **	2.475	0.015	0.524
2013	0.186 **	2.455	0.014	0.512
2014	0.187 **	2.460	0.013	0.506
2015	0.195 **	2.545	0.013	0.504
2016	0.205 ***	2.650	0.012	0.498
2017	0.215 ***	2.759	0.012	0.491
2018	0.213 ***	2.733	0.011	0.486

Note: ***, **, * indicate statistical significance of 99, 95, and 90%, respectively.

Moran's I of GDP over the 16-year period is always significantly positive, while that of IE is not significant. This shows that economic development has obvious spatial agglomeration characteristics. Since the efficiency of infrastructure investment is not an indicator of the real economy, it is difficult to form spatial dependence between regions, which is in line with the economic reality. Therefore, GDP was taken as the explanatory variable to study the spatial spillover effect of PPP. Model (7) was used, and the results are shown in Table 11.

Table 11. Spatial spillover effect of PPP.

Variables	Explained Variable: GDP				
	Coefficient			Effect	
	Local	Neighboring	Direct	Indirect	Overall
PPP	0.003 * (1.70)	0.007 * (1.84)	0.004 ** (2.09)	0.017 ** (2.19)	0.020 ** (2.36)
SU	1.541 *** (12.60)	−0.600 * (−1.84)	1.565 *** (12.47)	0.509 (0.83)	2.074 *** (3.12)
BU	−1.669 *** (−4.06)	1.962 * (1.69)	−1.498 *** (−3.55)	2.220 (0.94)	0.723 (0.28)
OP	−0.706 ** (−2.46)	1.207 * (1.94)	−0.617 ** (−2.01)	1.634 (1.24)	1.017 (0.68)
MI	0.052 *** (6.42)	−0.055 ** (−2.13)	0.049 *** (5.93)	−0.053 (−0.95)	−0.004 (−0.07)
CP	0.026 ** (2.29)	0.070 ** (2.15)	0.036 *** (3.01)	0.168 ** (2.53)	0.205 *** (2.84)
PO	−0.207 * (−1.82)	0.165 (0.72)	−0.204 * (−1.84)	0.106 (0.25)	−0.098 (−0.23)
ρ	0.536 *** (8.92)				
σ^2	0.005				
Year	Control				
Province	Control				
R ²	76.53%				
Log L	603.84				
N	496				

Note: Values in parentheses are t statistics. ***, **, * indicate statistical significance of 99, 95, and 90%, respectively. Results were processed by Stata 14.0.

The value of ρ is 0.536 and significantly positive, showing a strong regional economic agglomeration effect. In terms of the coefficients, the impact of each factor on local economic development is consistent with Table 9. The coefficients of neighboring areas show that PPP has a positive correlation with the economic development of neighboring areas, as does CP, which indicates that both PPP infrastructure investment and human capital have a positive spatial spillover effect, manifesting external economies. PO is no longer significant, so the population size does not have a spatial spillover effect, which is in line with the economic reality. Comparing the coefficients, the three kinds of effects can more accurately measure the extent to which each factor affects economic development. Direct, indirect, and overall effects reflect the impact degree of each factor on local, neighboring, and overall economic development, respectively. This paper focuses on explaining the direct and indirect effects. The coefficients of the direct effect are more significant compared to those of the indirect effect, indicating that local economic development is driven more by self-support and the contribution of spatial spillover benefits by neighboring areas is limited. In the indirect effect, only PPP and CP are still significantly positive, which further shows that PPP infrastructure investment and human capital have stronger positive spatial spillover effects compared with other factors. Hypothesis 3A can be confirmed.

4.5. Industrial Heterogeneity of PPP

In order to arrive at more comprehensive conclusions, the industry heterogeneity of PPP was further tested, as shown in Table 12.

Table 12. Industrial heterogeneity of PPP.

Variables	Explained Variable: GDP								
	Transportation			Energy			Water		
	Direct	Indirect	Overall	Direct	Indirect	Overall	Direct	Indirect	Overall
PPP	0.004 ** (2.22)	0.016 * (1.77)	0.020 ** (2.02)	0.002 (0.91)	0.018 ** (2.07)	0.020 ** (2.07)	0.002 (0.91)	0.022 * (1.93)	0.024 * (1.93)
SU	1.552 *** (12.36)	0.498 (0.81)	2.050 *** (3.07)	1.577 *** (12.52)	0.621 (0.99)	2.198 *** (3.23)	1.575 *** (12.54)	0.504 (0.81)	2.079 *** (3.09)
BU	−1.547 *** (−3.65)	1.991 (0.84)	0.444 (0.17)	−1.505 *** (−3.55)	1.595 (0.66)	0.090 (0.03)	−1.609 *** (−3.76)	1.660 (0.69)	0.051 (0.02)
OP	−0.649 ** (−2.11)	1.559 (1.18)	0.910 (0.61)	−0.606 ** (−1.97)	1.831 (1.35)	1.225 (0.80)	−0.628 ** (−2.04)	1.469 (1.10)	0.841 (0.56)
MI	0.047 *** (5.65)	−0.063 (−1.10)	−0.016 (−0.26)	0.050 *** (6.01)	−0.050 (−0.88)	−0.001 (−0.01)	0.048 *** (5.69)	−0.064 (−1.11)	−0.016 (−0.27)
CP	0.039 *** (3.26)	0.185 *** (2.78)	0.224 *** (3.12)	0.038 *** (3.12)	0.186 *** (2.76)	0.224 *** (3.07)	0.038 *** (3.12)	0.179 *** (2.66)	0.217 *** (2.97)
PO	−0.215 ** (−1.96)	0.026 (0.06)	−0.190 (−0.45)	−0.212 * (−1.92)	0.041 (0.10)	−0.171 (−0.40)	−0.233 ** (−2.15)	0.105 (0.24)	−0.128 (−0.29)
ρ	0.538 *** (8.95)			0.545 *** (9.16)			0.541 *** (9.03)		
σ^2	0.005			0.005			0.005		
Year	Control			Control			Control		
Province	Control			Control			Control		
R ²	76.82%			72.21%			74.82%		
Log L	603.62			603.10			602.76		
N	496			496			496		

Note: Values in parentheses are t statistics. ***, **, * indicate statistical significance of 99, 95, and 90%, respectively. Results were processed by Stata 14.0.

After distinguishing industries, the spatial spillover effect of economic development is still significantly positive, and the economic impact of PPP has significant industrial heterogeneity. The direct, indirect, and overall effects of transportation PPP are all significantly positive, indicating that PPP investment in transportation infrastructure not only promotes local economic development, but also creates great external economic benefits for the neighboring areas. PPP improves the regional transportation infrastructure interconnection to consolidate the material carrier foundation for sustainable economic development. The direct effect of energy and water PPP is not significant, but the indirect effect is significant; that is, energy and water PPP have positive external economy. Hypothesis 3B can be confirmed. All of this highlights the extreme importance of transportation infrastructure in the development of a national economy. Transportation infrastructure has become the most important material carrier to promote the flow of economic factors between regions and improve the quality of national economic growth. Therefore, mobilizing private parties to form long-term partnerships with the government to build a modern transportation system has become the general trend in China to ensure high-quality economic development.

5. Discussion

5.1. Evaluation of Infrastructure Input–Output Efficiency and Economic Development

The infrastructure input–output efficiency in China from 2003 to 2018 was measured by using SFA, showing that the overall efficiency is 0.449, far below 1, which is a state of inefficiency. In different regions, it has obvious heterogeneity and sequencing, presenting a distribution trend of decreasing from east (0.685) to west (0.283), consistent with findings from previous research [36,39,40]. The result is also basically in line with the ranking in the White Paper on China's Infrastructure Competitiveness Index (2020) released by the China Fujian Economic Information Center and the research institute of Tsinghua University. China's national conditions determine the imbalance of its regional economic

development. The level of economic development in eastern China is significantly higher than that in central and western China, and infrastructure is the main factor causing the regional differences [41]. The relationship between infrastructure investment and economic development is one of mutual influence and promotion [42]. Focusing on improving the regional layout of infrastructure investment will be essential for the sustainable and balanced development of China's regional economy. The results of this paper show that PPP is positively correlated with the input–output efficiency of infrastructure. This is different from previous research [9], in which the adopted efficiency evaluation method was nonlinear programming, so there are differences in the accuracy of efficiency calculation; the differential method was used to regard PPP as a policy impact and the impact of PPP investment was not studied. These may account for the difference in conclusions.

5.2. Economic Growth Effect of PPP

This paper confirms that PPP can boost economic development, which is consistent with China's policy orientation and the results of current theoretical studies. In recent years, China has actively introduced policies to promote the standardization and rationalization of PPP, making it innovate and develop in the direction of improving quality and efficiency. In March 2019, the Ministry of Finance issued a guideline that gave full play to the positive role of cooperation between the government and private party to promote high-quality economic development of China in the new era. China's 14th Five-Year Plan (2021–2025) once again clearly points to giving full play to the advantages of PPP to support the construction of major projects for the coordinated development of regional economy. Propelled by sound policies, the number and investment of PPP projects in China have achieved a sustained and stable growth trend, which is enough to show that the economic advantage of PPP has been affirmed by the governance layer.

Furthermore, most theoretical studies have recognized that PPP can promote economic development from the analysis aspects of governance mechanism, resource allocation, supply mode, and information efficiency of PPP. PPP is more reflected in the major innovation of public management mode and government governance mechanism in China's practice, which introduces the market mechanism to improve the infrastructure provision efficiency with its built-in advantage, thus to effectively promote economic development [43–45]. According to the principal-agent theory, PPP effectively alleviates the information asymmetry between the government and private party through contract, reduces principal-agent cost and solves the problem of adverse selection. Finally, the PPP data used in the empirical test of this paper are all successful infrastructure PPP projects, which play an indispensable role in China's economic and social development, which also confirms the rationality of the research results of this paper.

5.3. Spatial Spillover Effect and Industrial Heterogeneity of PPP

This paper shows that PPP has a positive spatial spillover effect and significant industrial heterogeneity, suggesting that PPP infrastructure investment can promote regional economic integration development and PPP in transportation can bring greater economic benefits. The research hypothesis is verified by empirical tests based on the theoretical analysis of the infrastructure network, externality, and the spatial dependence of the economy itself, consistent with findings from previous research [14]. Some studies point out that infrastructure investment has a positive spatial spillover effect [46,47], while others indicate a negative effect [29]. The spatial spillover effect of infrastructure has been confirmed by most studies; however, the effect is positive or negative depending on the industry and data used. To be sure, not every kind of investment can produce a positive spatial spillover effect, and identifying efficient investments is the key.

According to the above analysis, infrastructure investment includes not only single government investment, but also PPP investment, as well as separate investment from social capital. The efficiency and quality of different investment types are different, which is also the reason why PPP was selected in this paper. PPP not only has the economic benefits

of investment, but also the social benefits of infrastructure and the cooperative benefits of governments and private parties. Therefore, it can better reflect the efficiency of investment, which is also confirmed in the empirical test in Section 4.2. The conclusion that PPP can produce a positive spatial effect has theoretical support and necessary verification. In terms of the industrial heterogeneity of PPP, the advantages of investing in transportation infrastructure are apparent, which is in line with China's development strategy and the centrality of transportation, which is also widely verified by many studies on the positive role of transportation in regional economic development. The positive externalities of energy and water industries also reflect the public welfare characteristics of infrastructure investment and construction. Therefore, it is necessary to study PPP from the perspective of spatial economics, which will provide a new way of thinking and a new organization mode for its development and innovation in the future.

5.4. Necessity of Long-Term Planning and Investment in Infrastructure through PPP

In the backdrop of COVID-19 and the induced uncertainty of global socio-economic performance, infrastructure construction and investment are an important way to hedge against economic downturn and boost the economy [48], which has huge space for further development. However, the economic downturn has increased the burden on the government's finances, thus exacerbating the imbalance between supply and demand of infrastructure. In this situation, the investment from the social capital is particularly important, and PPP mode has become the inevitable choice [49]. The findings of this paper suggest that PPP can play a sustainable role in infrastructure construction and economic development, which is reflected in stable fund guarantee and efficient resource allocation, thus forming a long-term high-quality infrastructure supply mode [17]. At present, China is vigorously promoting the developmental PPP with regional space as the carrier and industrial development as the core so as to achieve sustainable development of regional economy. It follows that the realization of sustainable economic development under the regional virtuous circle driven by infrastructure investment through PPP is an irresistible general trend. This also highlights the necessity of long-term planning and investment in infrastructure through PPP in the case of economic uncertainty.

5.5. Limitations of the Study

This study has some potential limitations. First, limited by the availability of data from the World Bank PPI Database, the analysis of industrial heterogeneity of PPP only involves three main industries (transportation, energy, and water). Investigating other industries will be the direction of efforts in the future to explore further interesting conclusions, focusing on industry comparisons. Second, this paper focuses on the relationship between PPP and economic development without an in-depth exploration of the intervening influencing factors, which can be further studied. Third, since developmental PPP has just started to be practiced in China, its economic effects have not yet been verified by practice and theory. This will be worth paying attention to in future in-depth studies.

6. Conclusions

This paper takes data with Chinese characteristics as the research sample and empirically tests the impact of PPP on sustainable economic development based on two main research dimensions: evaluating infrastructure input–output efficiency and analyzing the spatial spillover effect. Regarding the former dimension, the input–output efficiency of infrastructure in China's 31 provinces from 2003 to 2018 is evaluated by SFA and regional development differences are discussed. Based on this, the sustainability of infrastructure investment and the economic efficiency of PPP are analyzed and validated. Regarding the latter dimension, taking GDP as the explanatory variable, the overall economic growth effect of PPP is tested. Furthermore, based on examining the spatial autocorrelation of economy, the spatial spillover effect of PPP and its industrial heterogeneity are tested.

The results reveal that PPP indeed plays an important role in promoting sustainable economic development in China, which is manifested in the following three aspects. First, PPP is positively correlated with the input–output efficiency of infrastructure and its impact is more significant than that of single government investment, indicating that PPP in infrastructure investment can play a sustainable role by leveraging less capital to achieve greater economic benefits. Second, PPP has an overall economic growth effect and spatial spillover effect. It not only drives local economic development, but also plays a synergistic role in driving the economic development of neighboring areas to achieve sustainable regional development. Third, the impact of PPP infrastructure investment in different industries varies significantly. Transportation PPP not only has a direct economic growth effect, but also a positive spatial spillover effect. Energy and water PPP have positive economic externalities. Therefore, transportation PPP plays a stronger role in driving the economy, which is determined by the vital position of transportation infrastructure. This is in line with China's strategy of building a country with a strong transportation network: develop the leveraging role of government investment, stimulate the vitality of social capital, drive the construction of major transportation projects with PPP, form network and integration effects, and continue to consolidate the carrier foundation for high-quality integrated regional development.

In the new era, how to make PPP realize greater efficiency for sustainable economic development and form a consensus and influence around the world has become a crucial proposition for its future development and innovation. One important aspect is to prioritize development and cooperation in the area of transport infrastructure. This involves not only the economic development of the country itself, but also the formation of effective cooperation among countries to use PPP as a bridge and to promote the interconnection of transportation infrastructure around the world, in order to lay a solid foundation and guarantee a win-win for all countries. Moreover, it is urgent and necessary to perfect the top-level design of PPP and cultivate a new value system from the perspective of coordinated regional development. Based on the main cycle of the domestic economy, we should improve regional policies and spatial layout, integrate PPP into the overall pattern of interconnected regional development, vigorously promote its development with the goal of sustainable regional development, and further introduce supporting policies and long-term cooperative mechanisms between governments and social capital. Developmental PPP has now become an important means of innovating regional development modes. Based on normative PPP operation, developmental PPP emphasizes the high-quality provision of comprehensive development and infrastructure with regional industrial layout and urbanization as the core, which becomes a new way to integrate old and new infrastructure and upgrade industries. It is still essential to test developmental PPP in practice, taking the Chinese experience as an example to be recognized in the world.

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To: Xuemeng Guo

School of Economics and Management, Beijing Jiaotong University, China

Dear Dr. Guo,

I am more than pleased to inform you that based on the recommendations of the referees, your paper titled

**Public-Private Partnership and Transport Infrastructure Investment Efficiency: Evidence from Countries along the
21st-Century Maritime Silk Road**

coauthored with

Bingyao Chen^{†*}, Xuemeng Guo

has been accepted for publication in the Journal of Coastal Research.

The paper will be scheduled in the special issue with ID SI 112, 2020, which is dated on November 2020.

Thank you very much for your contribution to this special issue of Journal of Coastal Research.

Sincerely Yours,

Chris Makowski

Editor in Chief of Journal of Coastal Research



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Public-Private Partnership and Transport Infrastructure Investment Efficiency: Evidence from Countries along the 21st-Century Maritime Silk Road

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ABSTRACT

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The 21st-Century Maritime Silk Road Initiative blazes a new path for countries to cooperate for mutual benefits, and transport infrastructure has become the main battlefield for investment. With data from 2000 to 2017, the research adopts Stochastic Frontier Analysis (SFA) to evaluate transport infrastructure investment efficiency of 20 countries along the route. The results show that the average investment efficiency is 0.552 which is in the state of inefficiency, exposing the problems of efficiency loss and resource waste, but still, a yearly increasing trend is evident. The investment efficiency of the developed countries is notably higher, revealing remarkable regional discrepancy and imbalance of development. The research also reveals the Public-Private Partnership (PPP) and the Initiative's positive effect on investment efficiency by empirical examinations. PPP has helped improve investment efficiency overall but PPP in different transport sectors has heterogeneous effect that road and port PPP can significantly promote investment efficiency. The Initiative has also boosted investment efficiency along the route, especially for developing countries. All this proves the superiority and necessity of PPP and the far-reaching significance of this valuable initiative for the sustainable development of all countries.

ADDITIONAL INDEX WORDS: *Marine economy development, social capital, transportation facilities performance, stochastic frontier analysis.*

INTRODUCTION

China's 21st-Century Maritime Silk Road Initiative has received worldwide attention since announced in 2013. By 2019, 65 countries have been participating states and transport infrastructure connectivity has become a priority development area with huge investment opportunities. According to the Global Infrastructure Center, global investment demand in transport services totaled 1.6 trillion dollars in 2019, among which a significant proportion came from countries along the Maritime Silk Road. Studies have also proved that the Initiative is of great value in promoting technical advancement (Chen and Fan, 2016), improving infrastructure performance (Li and Li, 2018), and boosting economic growth (Li, 2018; Ma *et al.*, 2019).

The World Bank defines PPP as a long-term contract between a private party and a government entity for providing a public asset or service. For years, PPP has been widely utilized in transport infrastructure to finance mega projects, and to increase market competition so as to reduce inefficiency caused by government monopoly (Yehoue, Hammami, and Ruhashyankiko, 2011). It can

also introduce technical and management expertise from private party to improve project efficiency (Moszoro and Gasiorowski, 2008; Shen, Platten, and Deng, 2006), helping form a long-term supply mode of high quality and efficiency (Liao, Liu, and Luo, 2018). As Cheng and Zheng (2019) highlighted, infrastructure construction adopting PPP forecasted a rosy prospect among countries along the Maritime Silk Road. However, the efficiency of PPP compared to traditional modes could only be testified under certain conditions; and PPP is not a panacea for all potential ills (Pei and Zeng, 2017; Yao and Li, 2015).

Previous studies have mostly adopted Data Envelopment Analysis (DEA) to evaluate urban infrastructure efficiency (Liu *et al.*, 2017; Ren, 2017), regional infrastructure efficiency (Liu, 2019) and infrastructure efficiency in an industry (He and Liu, 2020; Storto, 2011). Some studies also used regression analysis to investigate the economic benefits of infrastructure investment (Liao *et al.*, 2018). Scant attention has been devoted to the effect of PPP. In the light of Trujillo *et al.* (2002), the participation of the private party in transport infrastructure could contribute to per-capita income. Similarly, Cai (2019) found that PPP was significantly positively correlated with the infrastructure efficiency and that the involvement of private capital could boost social welfare. Mei and Luo (2019) further pointed out that PPP remarkably improved the static supply efficiency of public

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infrastructure. Yet Wang, Zuo, and Li (2019) came to the opposite conclusion that PPP's promotion of China's infrastructure efficiency was insignificant.

In summary, Chinese and foreign scholars have carried out a large number of studies, while there is still room for improvement. DEA bases on linear programming to calculate efficiency, thus easily producing decision-making units of which the efficiency is 1; and the results are prone to be of low precision and instability as the large size of samples fail to satisfy the calculation assumptions. Besides, most empirical studies regarded PPP simply as a policy shock without further investigating by multi-dimensional measurements, therefore generating vastly different and incomplete conclusions. Hence, the research adopts a more precise method, *i.e.* Stochastic Frontier Analysis, to evaluate the investment efficiency of transport infrastructure, further examines the effects of PPP and the Initiative, which provides the basis for validating the effectiveness of PPP and the practical value of the 21st-century Maritime Silk Road Initiative, and hopes to offer

some insights into the practice of PPP in the Maritime Silk Road area.

INVESTMENT EFFICIENCY EVALUATION

In economics, efficiency refers to the state that reaches the production-possibility frontier (the curve formed by the maximum output combination under the given input). Production frontier methods SFA and DEA are two most widely used methods to evaluate efficiency. Both measure the gap between the output of each individual and the maximum output combination to calculate the individual efficiency. Whilst DEA is a non-parametric method based on linear programming, SFA is parametric and production-function-based. By contrast, SFA has stricter requirements for models and performs better with large samples, considers the impact of random factors on output and has more realistic theoretical assumptions (Aigner, Lovell, and Schmidt, 1997; Meeusen and Broeck, 1997), and can adopt flexible function forms for different objects, allowing the results to be more targeted,

Table 1. *Investment efficiency of transport infrastructure.*

Gro- up	Country	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Country Average	Group Average
D e v e l o p e d	Slovenija	0.918	0.921	0.924	0.927	0.930	0.933	0.936	0.938	0.941	0.943	0.945	0.947	0.950	0.952	0.954	0.955	0.957	0.959	0.941	0.722
	Czech	0.720	0.730	0.740	0.749	0.758	0.767	0.775	0.784	0.792	0.799	0.807	0.814	0.821	0.828	0.834	0.841	0.847	0.853	0.792	
	Slovakia	0.680	0.691	0.701	0.712	0.722	0.732	0.741	0.751	0.760	0.768	0.777	0.785	0.793	0.801	0.808	0.815	0.822	0.829	0.760	
	Hungary	0.587	0.600	0.613	0.626	0.638	0.650	0.662	0.673	0.685	0.696	0.706	0.716	0.726	0.736	0.746	0.755	0.764	0.772	0.686	
	Estonia	0.513	0.527	0.542	0.556	0.569	0.583	0.596	0.609	0.622	0.634	0.646	0.658	0.670	0.681	0.692	0.703	0.713	0.723	0.624	
	Latvia	0.402	0.418	0.433	0.448	0.464	0.479	0.494	0.508	0.523	0.537	0.551	0.565	0.579	0.592	0.605	0.618	0.630	0.643	0.527	
	Turkey	0.954	0.956	0.957	0.959	0.961	0.962	0.964	0.965	0.967	0.968	0.969	0.971	0.972	0.973	0.974	0.975	0.976	0.977	0.967	
	Poland	0.712	0.722	0.732	0.742	0.751	0.760	0.769	0.777	0.785	0.793	0.801	0.808	0.815	0.822	0.829	0.836	0.842	0.848	0.786	
	Croatia	0.546	0.560	0.573	0.587	0.600	0.613	0.626	0.638	0.650	0.662	0.673	0.684	0.695	0.706	0.716	0.726	0.736	0.745	0.652	
	Russia	0.467	0.482	0.497	0.512	0.526	0.541	0.555	0.568	0.582	0.595	0.608	0.621	0.633	0.646	0.657	0.669	0.680	0.691	0.585	
D e v e l o p i n g	China	0.451	0.467	0.482	0.496	0.511	0.526	0.540	0.554	0.568	0.581	0.595	0.608	0.620	0.633	0.645	0.657	0.668	0.680	0.571	0.479
	Lithuania	0.424	0.439	0.455	0.470	0.485	0.500	0.514	0.529	0.543	0.557	0.571	0.584	0.597	0.610	0.623	0.635	0.647	0.659	0.547	
	Romania	0.366	0.381	0.397	0.413	0.428	0.444	0.459	0.474	0.489	0.504	0.518	0.533	0.547	0.561	0.574	0.588	0.601	0.614	0.494	
	India	0.286	0.301	0.316	0.332	0.347	0.363	0.379	0.394	0.410	0.425	0.441	0.456	0.471	0.486	0.501	0.516	0.530	0.544	0.417	
	Serbia	0.262	0.277	0.292	0.307	0.323	0.338	0.354	0.370	0.385	0.401	0.416	0.432	0.447	0.463	0.478	0.493	0.507	0.522	0.393	
	Bulgaria	0.233	0.247	0.262	0.277	0.292	0.308	0.323	0.339	0.354	0.370	0.386	0.401	0.417	0.432	0.448	0.463	0.478	0.493	0.362	
	Albania	0.210	0.224	0.238	0.253	0.268	0.283	0.298	0.314	0.329	0.345	0.361	0.376	0.392	0.407	0.423	0.438	0.454	0.469	0.338	
	Azerbaijan	0.112	0.123	0.134	0.146	0.158	0.171	0.184	0.197	0.211	0.225	0.240	0.254	0.269	0.284	0.300	0.315	0.331	0.346	0.222	
	Georgia	0.112	0.123	0.134	0.146	0.158	0.171	0.184	0.197	0.211	0.225	0.240	0.254	0.269	0.284	0.300	0.315	0.331	0.346	0.222	
	Moldova	0.068	0.076	0.085	0.094	0.104	0.114	0.125	0.136	0.148	0.160	0.173	0.186	0.200	0.213	0.228	0.242	0.257	0.272	0.160	
Annual Average		0.451	0.463	0.475	0.488	0.500	0.512	0.524	0.536	0.548	0.559	0.571	0.583	0.594	0.606	0.617	0.628	0.639	0.649	0.552	

accurate and reliable (He, Chen, and He, 2004). Accordingly, SFA is adopted.

Model Development

Cobb-Douglas (C-D) function and Trans-Log function are usually adopted in SFA. Viewing that the infrastructure investment system is a multiobjective, multivariate and nonlinear input-output system (Ren, 2017), the assumption of constant returns to scale in C-D function does not apply, while the Trans-Log function is more in line with the economic facts (Chen and Fan, 2016). Based on time-varying model (Battese and Coelli, 1992), the research chooses logarithmic Trans-log function to build the model, which is proven eligible as it has passed the statistical test.

$$\ln Y_{it} = \beta_0 + \beta_1 \ln K_{it} + \beta_2 \ln L_{it} + \beta_3 t + 1/2 \beta_4 (\ln K_{it})^2 + 1/2 \beta_5 (\ln L_{it})^2 + 1/2 \beta_6 t^2 + \beta_7 \ln K_{it} \ln L_{it} + \beta_8 t \ln K_{it} + \beta_9 t \ln L_{it} + v_{it} - u_{it} \quad (1)$$

$$u_{it} = e^{-\eta(t-T)} u_i \quad (2)$$

In formula (1), Y_{it} stands for output, K_{it} for capital input, L_{it} for labor input, β_1 for capital output elasticity, and β_2 for labor output elasticity; $v_{it} - u_{it}$ is the error term, $u_{it} \geq 0$ denotes the impact only on an individual.

In formula (2), η is time-varying coefficient. $\eta > 0$ indicates improvement of efficiency over time.

Efficiency is defined as:

$$TE_{it} = e^{-u_{it}} \quad (3)$$

When $u = 0$ and $TE = 1$, the individual output is equal to the maximum output and there is in the state of efficiency. $u > 0$ and $0 < TE < 1$ indicates that the individual output is less than the maximum output and there is in the state of inefficiency.

Data and Results

The GDP of 20 countries is selected as output, the investment in transport infrastructure (railway, road, port and airport) as capital input, and the number of employees in transport industry as labor input. All data come from World Bank database, OECD database and China Statistical Yearbook.

Table 1 showcases the investment efficiency of transport infrastructure and the countries are grouped into the developed ones and developing ones. From 2000 to 2017, the average investment efficiency is 0.552, suggesting the state of inefficiency, but a yearly increasing trend is evident. The average investment efficiency of the developed countries is 0.722, far higher than the 0.479 of the developing countries, which reveals remarkable regional discrepancy and imbalance of development. Note that Turkey, a developing nation, tops the list of the average investment efficiency (0.967). This could essentially boil down to its geographical position (linking Asia and Europe), convenient transportation, free investment environment and sustained investment stimulus plan. From 2003 to 2018, Turkey has attracted a total of approximately 209 billion dollars from overseas. Statistics from the World Bank showed that, in 2015, seven PPP projects of Turkey totaled 44.7 billion dollars, which attracted forty percent of global investment in social capital. As one of the least developed European country, Moldova's average investment efficiency is only 0.160. This could be attributed to its agriculture-dominated underdeveloped economy and years of political conflicts and economic crises.

EMPIRICAL ANALYSIS

In this section, PPP is subdivided into three dimensions to comprehensively investigate its overall effect on transport infrastructure investment efficiency, and the heterogeneous effect of PPP in railway, road, port and airport sectors is explored. Besides, the positive effect of the 21st-Century Maritime Silk Road Initiative is also validated.

Data, Variables and Model

(a) Data. The PPP data of transport infrastructure come from PPI database. Countries' economic statistics are from World Bank database and OCED database.

(b) Variables. The investment efficiency of transport infrastructure is taken as the explained variable, PPP and the Initiative as explanatory variables, urbanization level, financial development, opening-up degree, industrial structure and economic growth as control variables. Table 2 presents variables' measurements and descriptive statistics.

Table 2. Descriptive statistics.

Variable Symbol	Variable Measurement	Mean Value	Standard Deviation	Minimum Value	Maximum Value
IE	Transport infrastructure investment efficiency	0.5523	0.2345	0.0682	0.9772
PPP_1	Transport infrastructure PPP implementation or not	0.2250	0.4182	0	1
PPP_2	Transport infrastructure PPP projects number	1.9056	7.3781	0	73
PPP_3	Transport infrastructure PPP investment (logarithm)	4.5467	8.5258	0	24.3273
MSR	The 21st-Century Maritime Silk Road Initiative	0.2222	0.4163	0	1
MS	Financial development: broad money/GDP	57.9348	35.4072	10.3824	209.4513
OP	Opening-up: (import + export) / GDP	82.2015	37.1332	19.3130	176.1544
IND	Industrial structure: secondary industry/ service industry	0.5323	0.1557	0.2163	0.9467
UR	Urbanization: urban population/ total population	58.5367	11.3966	27.6670	74.6690
EC	Economic growth: growth rate of GDP per capita	4.5623	4.6053	-14.2688	32.9971

Table 3. Overall effect of PPP.

Explained Variable: IE								
Variables	1	2	Variables	3	4	Variables	5	6
PPP_1	0.0455*** (3.29)	0.0158** (1.99)	PPP_2	0.0013* (1.84)	0.0008** (2.09)	PPP_3	0.0025*** (3.45)	0.0008* (1.91)
MS		0.0035*** (10.72)	MS		0.0035*** (10.63)	MS		0.0035*** (10.68)
OP		0.0007*** (3.56)	OP		0.0007*** (3.28)	OP		0.0007*** (3.56)
IND		-0.0917* (-1.77)	IND		-0.1315** (-2.53)	IND		-0.0958* (-1.86)
UR		0.0038*** (3.32)	UR		0.0038*** (3.35)	UR		0.0038*** (3.28)
EC		-0.0019*** (-3.01)	EC		-0.0017*** (-2.82)	EC		-0.0019*** (-3.02)
$Cons$		0.0896 (1.30)	$Cons$		0.1165* (1.68)	$Cons$		0.0943 (1.37)
N	360	263	N	360	263	N	360	263
R^2	3.10%	71.74%	R^2	0.99%	71.79%	R^2	3.39%	71.70%

Note: The values in parentheses are t values; ***, **, * respectively indicate statistically significance of 99%, 95%, and 90%; the estimated results were processed by Stata14.0 and the same below.

(c) Model. According to the results of the Hausman test, the panel fixed effect model is adopted.

$$IE_{it} = \alpha_0 + \alpha_1 PPP_{nit} + \alpha_2 Control_{it} + \varepsilon_{it} \quad (4)$$

$$IE_{it} = \beta_0 + \beta_1 MSR_{it} + \beta_2 Control_{it} + \varepsilon_{it} \quad (5)$$

In formula (4) and (5), IE_{it} stands for the investment efficiency of transport infrastructure. There are three measures of PPP_n : PPP_1 is a dummy variable for PPP's implementation, values 1 for implementation and 0 for non-implementation; PPP_2 is the number of PPP projects; PPP_3 is the investment amount of PPP projects. MSR_{it} is a dummy variable of the Initiative. 2013 is taken as the node before which MSR_{it} values 0 and after which values 1. $Control_{it}$ represents a collection of control variables. ε_{it} represents the error term. α_1 and β_1 respectively measure the net effects of PPP and the Initiative on investment efficiency.

Examinations and Results

Results of PPP's overall and heterogeneous effect are respectively displayed in Table 3 and 4.

Above all, a significantly positive correlation between PPP and the investment efficiency is discovered, which suggests the positive effect of PPP. It is noteworthy that the development of the service industry has made greater contribution to the investment efficiency than that of the secondary industry. And the rapid growth of economy could provide smooth financing channels and

Table 4. Heterogeneous effect of PPP.

Explained Variable: IE						
Explanatory Variable	Sectors	Coef.	t	N	R^2	
PPP Implementation (PPP_1)	Road	0.0224**	2.32	263	71.90%	
	Port	0.0174**	2.22	263	71.85%	
	Railway	-0.0128	-1.18	263	71.44%	
	Airport	0.0050	0.60	263	71.32%	
	Road	0.0008*	1.92	263	71.71%	
PPP Projects Number (PPP_2)	Port	0.0059**	2.21	263	71.84%	
	Railway	-0.0038	-0.54	263	71.31%	
	Airport	0.0026	0.48	263	71.30%	
	Road	0.0011**	2.29	263	71.89%	
PPP Investment Amount (PPP_3)	Port	0.0010**	2.34	263	71.91%	
	Railway	-0.0008	-1.48	263	71.53%	
	Airport	0.0004	0.91	263	71.37%	

Note: The results are after adding control variables and the significance of the control variables are consistent with the full sample test, so they are not listed.

Table 5. *Effect of the 21st-century maritime silk road initiative.*

Variables	Explained Variable: <i>IE</i>					
	Panel A: Full Samples		Panel B: Developed Countries		Panel C: Developing Countries	
	1	2	3	4	5	6
<i>MSR</i>	0.1039*** (16.71)	0.0459*** (7.85)	0.0812*** (8.38)	0.0195** (2.47)	0.1136*** (14.61)	0.0495*** (7.58)
<i>MS</i>		0.0029*** (9.49)		0.0005 (0.78)		0.0031*** (9.35)
<i>OP</i>		0.0006*** (3.15)		0.0006** (1.99)		0.0008*** (3.26)
<i>IND</i>		-0.0469 (-1.01)		-0.4604*** (-3.55)		-0.0396 (-0.80)
<i>UR</i>		0.0029*** (2.83)		0.0099*** (5.36)		0.0019* (1.69)
<i>EC</i>		-0.0017*** (-3.06)		-0.0007 (-0.55)		-0.0018*** (-2.93)
<i>Cons</i>		0.1556** (2.50)		0.2015 (1.03)		0.1605** (2.52)
<i>N</i>	360	263	108	36	252	227
<i>R</i> ²	45.17%	77.11%	41.02%	94.91%	47.37%	76.96%

sound social environments, which partly reduces the spillover effect of PPP.

PPP in different transport sectors has exerted heterogeneous effect. Whilst the coefficients of port and road are remarkably positive, those of railway and airport are respectively insignificantly negative and positive. This suggests that PPP in road and port can significantly improve the investment efficiency. Only 32 railway PPP projects were implemented by the sample countries in 18 years, yet the average investment amount of railway was up to 1138 million dollars in comparison with an average of 260 million dollars for road and 218 million dollars for port. Due to the massive investment, longer construction period and investment payback period, railway infrastructure is difficult to output performance in a short time. The number of airport PPP projects was only 43 in contrast to 504 for road and 111 for port, making the scale effect of airport PPP less significant compared to those of road and port. Moreover, the development degree of these 20 countries varies greatly. The road and port infrastructures require relatively low investments, and have therefore attracted more developing economies to invest. Survey showed that the 20 countries greater connectivity by ports than by other transport facilities as maritime services were available among all these coastal countries. This adequately justifies the paramount significance of ports to countries along the route in trade cooperation and economic development.

Results of the Initiative's effect are displayed in Table 5.

All MSR coefficients are significantly positive, which implies that this Initiative has greatly improved the investment efficiency of transport infrastructure in the 20 countries, hence validating the practical value of the Initiative. Grouping test shows that

the MSR coefficient of the developing countries is higher than that of the developed countries, suggesting that the Initiative is more effective in helping improve the investment efficiency of developing countries. One reason is that developing countries have lower investment cost and higher degree of improvement of transport infrastructure, thus opening up more opportunities and appreciation space for investors. Another reason is that the connectivity in finance and other areas has provided developing countries with unprecedented accesses to resources, including capital, technology and innovation, all of which are important driving force for their sustainable development.

CONCLUSIONS

(a) From 2000 to 2017, the investment in transport infrastructure of all the 20 countries has not reached the state of efficiency, with varying degrees of efficiency loss and resource waste. And there is a great regional discrepancy and imbalance of development between developed and developing countries, with the former showcasing higher efficiency than the latter. Countries of higher investment efficiency enjoy more stable economy, sounder institutional environment, and better transportation, all of which pave way for the involvement of high-quality investment and the improvement of efficiency.

(b) PPP has a positive overall effect on the improvement of investment efficiency of transport infrastructure, but such effect is heterogeneous in different sectors, that is, road and port PPP notably promotes transport infrastructure investment efficiency, while railway exerts a negative impact. This is because different types of transport infrastructure are of different economic natures and obey different laws of development. Railway anticipates

larger investment, longer period of construction, thus less likely to make notable profits within a relatively short time. In summary, infrastructure construction should take into account both economic and social benefits. Unlimited investment in pursuit of efficiency and harming the interests of private party for government achievements are both unwise. Only by focusing on the actual economic needs and the good-quality PPP projects can bring forth positive scale and external effects, creating a win-win situation between the government and the private party.

(c) The 21st-Century Maritime Silk Road Initiative has played a critical role in stimulating the investment efficiency, especially for developing countries. The Initiative effectively contributes to the connectivity between developed and developing economies, alleviated the shortage of funds, and promoted the exchanges of advanced experience and technology. All these provided countries along the route, in particular the developing ones, with important financing channels and mechanism to safeguard resources.

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全要素生产率的测度与国际比较

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摘 要:文章运用随机前沿模型测度我国及主要创新型国家2001—2018年的全要素生产率,并探究全要素生产率的影响因素,揭示关键要素对我国全要素生产率的影响规律。研究发现:我国全要素生产率与创新型国家相比仍有进步空间,但逐年提高的改善趋势已经显现,与创新型国家平均水平的相对差距稳步缩小。我国要素投入呈现资源利用率提高的趋势特征,体现出投入产出动态平衡的良性发展态势。不同要素对我国全要素生产率的影响效应与规律存在差异性、层级性,第三产业的主导作用越来越强,科技经费与人力投入发挥了稳定持续的提升作用。

关键词:全要素生产率;高质量发展;随机前沿分析

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0 引言

党的十九大报告首次提出“提高全要素生产率”。“十四五”规划明确构建中国经济发展新格局,以提高全要素生产率,推动经济高质量发展。全要素生产率作为判断经济体增长质量和发展潜力的一项重要标准,体现了“集约式增长”的发展理念,契合了我国以创新驱动高质量发展的深刻内涵。准确把握全要素生产率的内涵实质,科学测度全要素生产率并厘清其影响因素,是探索全要素生产率提升路径的重要前提。“生产率”一词最早提出于1766年,《英国大百科全书》将其定义为“生产所得与生产这些所需之比”。Cobb和Douglas(1928)^[1]创造的C-D生产函数开创了生产率定量研究的先河,通过阐释经济产出与资本、劳动投入之间的关系,奠定了全要素生产率的概念前提。Tinbergen(1942)^[2]进一步研究除资本、劳动外其他要素对经济增长的影响,将研究视角由单要素拓展至多要素,正式提出“全要素生产率”这一表述。Solow(1956)^[3]认为经济体间的产出差距不能由资本、劳动等有形要素投入的增长来完全解释,并把产出增长率扣除有形要素增长率后的剩余部分解释为技术进步率,进一步丰富了全要素生产率的内涵。OECD在《生产率测算手册》中,将全要素生产率定义为所有投入要素对产出增长贡献的能力。综上所述,可以将全要素生产率的内涵概括为:在资本、劳动等有形要素投入水平既定的条件下所达到的额外生产效率,其本质上反映的是要素投入与产出之间的动态平衡关系与资源配置效率。已有研究集中在全要素生产率的测度,

涵盖国家层面^[4-6]、区域层面^[7,8]、产业层面^[9],以及各类测度方法的辨析与优化^[10,11]。

目前,全要素生产率多以单一主体为测度对象,缺乏基于比较视野的定量研究,难以反映不同主体间的效率差异从而制定科学的目标依据。另外,已有研究对全要素生产率的内涵尚未达成共识,使用的测度方法也不尽相同,导致结果差异较大、可比性较弱。因此,本文以国际比较为切入点,采用随机前沿模型测度世界18个创新型国家与我国2001—2018年的全要素生产率,基于可比性原则分析国家间的相对效率差异,进而从“形”和“势”两个维度研究不同要素对于全要素生产率的影响效应与规律,旨在为科学评价我国全要素生产率、厘清提高全要素生产率的关键要素提供参考依据。

1 全要素生产率的测度与分析

随机前沿分析(SFA)和数据包络分析(DEA)是测度全要素生产率的主流方法,其原理是根据样本中所有个体的投入与产出构造生产前沿面,衡量个体实际产出与生产前沿面之间的距离,求解个体效率。一个样本点全要素生产率的变化,可以分解为该样本点技术效率的变化和未体现的技术进步两部分,以横截面数据所测得的个体技术效率,反映了该个体同生产前沿面的全要素生产率之差,此时个体技术效率等同于全要素生产率^[6,12]。SFA和DEA的区别在于,SFA是基于生产函数的参数方法,DEA是基于线性规划的非参数方法。SFA对模型与数据的要求更为严格,适合大样本分析,考虑了随机因素对产出的影响,具

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有更现实的理论假设^[13],可根据研究对象性质灵活选择生产函数形式,对模型适用性、参数时变性进行统计检验,使测度结果更具针对性与准确性^[8]。因此,本文采用SFA来测度2001—2018年各国的全要素生产率。

1.1 模型设计

SFA常用的生产函数为C-D函数和Trans-log函数,前者假设规模报酬不变,后者则克服了这一缺点。由于社会经济系统是一个多目标、多变量、非线性的综合体,因此采用Trans-log函数更符合经济实际。本文根据 Battese 和 Coelli (1992)^[14]的时变模型的基本原理,构建Trans-log函数模型如下:

$$\ln Y_{it} = \alpha_0 + \alpha_1 \ln K_{it} + \alpha_2 \ln L_{it} + \alpha_3 t + 1/2 \alpha_4 (\ln K_{it})^2 + 1/2 \alpha_5 (\ln L_{it})^2 + 1/2 \alpha_6 t^2 + \alpha_7 \ln K_{it} \ln L_{it} + \alpha_8 t^* \ln K_{it} + \alpha_9 t^* \ln L_{it} + v_{it} - u_{it} \quad (1)$$

式(1)中, Y_{it} 表示产出, K_{it} 表示资本投入, L_{it} 表示劳动力投入, $v_{it} - u_{it}$ 为复合误差项。

$$u_{it} = e^{-\eta(t-T)} u_i \quad (2)$$

式(2)中, η 为时变系数, $\eta > 0$ 说明生产率具有随时间推移的提升趋势,反之亦然。

定义全要素生产率为:

$$TFP_{it} = e^{-u_{it}} \quad (3)$$

式(3)中,当 $u=0$ 时, $TFP=1$,此时个体实际产出等于最大产出,处于完全效率状态; $u > 0$, $0 < TFP < 1$,此时个体实际产出小于最大产出,处于效率损失状态。

1.2 样本选取与数据说明

本文选取美国、英国、德国、日本、法国、芬兰、俄罗斯、意大利、以色列、加拿大、澳大利亚、韩国、捷克、瑞士、瑞典、奥地利、丹麦、新加坡这18个创新型国家和中国作为研究样本,选用2001—2018年各国的2010年不变价GDP作为产出变量,2010年不变价资本形成总额作为资本投入变量,就业人口数量作为劳动力投入变量。各国经济数据取自世界银行数据库、OECD数据库和历年《中国统计年鉴》。

1.3 结果分析

模型参数估计与检验结果见表1。多数系数通过了显著性检验且似然比检验值在1%的水平上显著,表明模型稳健有效。 $\gamma = 0.999$,接近于1,说明误差项具有十分明显的复合结构,采用SFA而非线性规划来分析这一面板数据是有必要的。

表1 模型参数估计与检验结果

参数	系数	t值
α_0	11.377***	4.179
α_1	1.253***	3.689
α_2	-0.935***	-3.621
α_3	-0.169***	-8.796
α_4	0.086***	4.292
α_5	-0.006	-0.308
α_6	-0.001***	-5.387
α_7	0.069***	5.127
α_8	0.014***	12.778
α_9	-0.011***	-10.060
γ	0.999***	4665.061
η	0.029***	25.891
对数似然函数值	807.612***	
似然比检验值	1314.163***	

注:***、**、*分别表示在1%、5%、10%的水平上显著。下同。

$\eta = 0.029 > 0$,说明全要素生产率随时间推移呈现明显的提升趋势。

各国2001—2018年全要素生产率的测度结果见表2。样本国家18年的平均全要素生产率为0.683,其中18个世界创新型国家的平均值为0.715,美国位列第一,平均达到0.945,其次为瑞士、法国、意大利、德国、日本、英国等。我国全要素生产率与世界主要创新型国家相比存在一定差距,仍有提升空间。值得说明的是,本文基于SFA测度的全要素生产率是相对效率而非实际值,反映的是各国之间的对比关系,展现出的持续提高趋势本质上属于一种相对增长。据国家统计局统计,“十三五”期间,世界创新型国家的全要素生产率平均达到70%,德国和美国超过了80%。吴先华等(2011)^[4]采用C-D生产函数测度了世界主要国家1999—2006年的全要素生产率,本文与其结论基本一致。以上均提供了相应佐证,说明本文的测度结果符合客观实际。

表2 2001—2018年世界主要创新型国家与我国的全要素生产率

国家	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	均值
美国	0.931	0.933	0.934	0.936	0.938	0.940	0.941	0.943	0.944	0.946	0.947	0.949	0.950	0.952	0.953	0.954	0.956	0.957	0.945
瑞士	0.887	0.890	0.893	0.895	0.898	0.901	0.904	0.906	0.909	0.911	0.914	0.916	0.918	0.920	0.923	0.925	0.927	0.929	0.909
法国	0.838	0.843	0.847	0.851	0.855	0.858	0.862	0.866	0.869	0.873	0.876	0.879	0.882	0.886	0.889	0.891	0.894	0.897	0.870
意大利	0.838	0.842	0.846	0.850	0.854	0.858	0.861	0.865	0.868	0.872	0.875	0.879	0.882	0.885	0.888	0.891	0.894	0.897	0.869
德国	0.801	0.806	0.811	0.816	0.820	0.825	0.829	0.834	0.838	0.842	0.846	0.850	0.854	0.858	0.862	0.865	0.869	0.872	0.839
日本	0.789	0.795	0.800	0.805	0.810	0.815	0.819	0.824	0.828	0.833	0.837	0.841	0.845	0.849	0.853	0.857	0.861	0.864	0.829
英国	0.786	0.792	0.797	0.802	0.807	0.812	0.817	0.821	0.826	0.830	0.835	0.839	0.843	0.847	0.851	0.855	0.859	0.863	0.827
澳大利亚	0.779	0.784	0.790	0.795	0.800	0.805	0.810	0.815	0.820	0.824	0.829	0.833	0.837	0.842	0.846	0.850	0.854	0.857	0.820
丹麦	0.750	0.756	0.762	0.768	0.773	0.779	0.785	0.790	0.795	0.800	0.805	0.810	0.815	0.820	0.824	0.829	0.833	0.838	0.796
加拿大	0.740	0.746	0.752	0.758	0.764	0.770	0.775	0.781	0.787	0.792	0.797	0.802	0.807	0.812	0.817	0.821	0.826	0.830	0.788
瑞典	0.716	0.723	0.730	0.736	0.743	0.749	0.755	0.761	0.767	0.772	0.778	0.784	0.789	0.794	0.799	0.805	0.809	0.814	0.768
奥地利	0.637	0.645	0.653	0.661	0.668	0.676	0.683	0.691	0.698	0.705	0.712	0.719	0.726	0.732	0.739	0.745	0.751	0.757	0.700
芬兰	0.604	0.612	0.621	0.629	0.637	0.645	0.653	0.661	0.669	0.677	0.684	0.691	0.699	0.706	0.713	0.720	0.726	0.733	0.671
以色列	0.497	0.506	0.516	0.526	0.536	0.545	0.554	0.564	0.573	0.582	0.591	0.600	0.608	0.617	0.625	0.634	0.642	0.650	0.576
新加坡	0.485	0.495	0.505	0.515	0.524	0.534	0.544	0.553	0.562	0.571	0.580	0.589	0.598	0.607	0.616	0.624	0.632	0.641	0.565
韩国	0.344	0.354	0.365	0.375	0.385	0.396	0.406	0.417	0.427	0.438	0.448	0.458	0.468	0.478	0.488	0.498	0.508	0.518	0.432
捷克	0.285	0.295	0.305	0.316	0.326	0.337	0.347	0.358	0.368	0.379	0.389	0.399	0.410	0.420	0.431	0.441	0.451	0.462	0.373
俄罗斯	0.209	0.218	0.228	0.237	0.247	0.257	0.267	0.277	0.287	0.298	0.308	0.318	0.329	0.339	0.350	0.360	0.371	0.381	0.293
中国	0.055	0.059	0.064	0.069	0.075	0.081	0.086	0.093	0.099	0.106	0.113	0.120	0.127	0.135	0.142	0.150	0.159	0.167	0.106
均值	0.630	0.636	0.643	0.649	0.656	0.662	0.668	0.675	0.681	0.687	0.693	0.699	0.705	0.710	0.716	0.722	0.727	0.733	0.683

2 全要素生产率的影响因素分析

全要素生产率的提高是各类经济要素共同作用、相互协调的结果,有必要对其进行进一步的解释分析,厘清各类要素对全要素生产率的影响效应、程度与趋势。已有研究主要从技术投入、人力资本、市场贸易、制度政策等角度对全要素生产率进行分解,发现R&D经费投入、人力资本水平、对外开放程度、市场化程度、改革制度变迁等对全要素生产率具有正向影响^[15-17]。在前人研究基础上,本文以可得各国经济数据为范围,基于数据准确完整的前提,对各类要素进行筛选与检验,探究全要素生产率的影响因素。

2.1 数据、变量与模型

(1)数据与变量。以测得的全要素生产率作为被解释变量,选取R&D经费投入强度、R&D研究人员数量、产业结构、人力资本水平、金融发展程度、城市化水平、对外开放程度、外商直接投资作为解释变量(见表3)。各国经济数据取自世界银行数据库、OECD数据库、历年《中国统计年鉴》。

表3 变量描述性统计

变量	符号	测度	观测值	平均值	标准差	最小值	最大值
全要素生产率	TFP	本文测得	342	0.683	0.230	0.055	0.957
R&D经费投入强度	$R\&D$	R&D经费投入/GDP	318	2.436	0.902	0.940	4.953
R&D研究人员数量	RE	取自然对数	290	8.243	0.531	6.349	8.995
产业结构	IND	第二产业产值占GDP比重/第三产业产值占GDP比重	342	0.368	0.141	0.189	0.839
人力资本水平	HR	高等教育毛入学率	246	67.010	18.890	9.789	121.00
金融发展程度	MS	广义货币供应量/GDP	240	109.400	50.590	23.910	252.900
城市化水平	UR	城镇人口/总人口	342	78.730	11.520	37.090	100.000
对外开放程度	OP	进出口总额/GDP	342	66.710	55.270	17.310	343.500
外商直接投资	FDI	外商投资净流入/GDP	342	3.597	5.162	-10.810	28.600

(2)模型设计。根据Hausman检验结果,本文采用双向固定效应模型:

$$TFP_{it} = \beta_0 + \beta_1 R\&D_{it} + \beta_2 RE_{it} + \beta_3 IND_{it} + \beta_4 HR_{it} + \beta_5 MS_{it} + \beta_6 UR_{it} + \beta_7 OP_{it} + \beta_8 FDI_{it} + \delta_i + \theta_t + \varepsilon_{it} \quad (4)$$

式(4)中, TFP_{it} 表示 i 国家 t 年份的全要素生产率,系数 β_1 至 β_8 分别度量了各要素对全要素生产率的影响净效应。 δ_i 、 θ_t 为个体和时间固定效应, ε_{it} 为随机干扰项。

2.2 影响效应分析

各类要素对全要素生产率的影响效应见表4。 $R\&D$ 系数始终显著为正,说明 $R\&D$ 经费投入强度的提高促进了全要素生产率的提升; RE 系数总体显著为正,说明 $R\&D$ 研究人员数量的增长亦具有提升效应; $R\&D$ 和 RE 从狭义科技进步视角度量了科技经费和人力投入对全要素生产率的贡献,体现了以科技创新驱动高质量发展的内涵。 IND 系数始终显著为负,表明第三产业对全要素生产率的提升作用明显大于第二产业,这与我国产业结构的

演进历程、经济增长的动力转换是相匹配的。随着中国经济步入新常态,拉动经济增长的动力因素发生了结构性变化。根据国家统计局数据,2014年,我国第三产业占GDP的比重首次超过第二产业,标志着中国经济正式迈入“服务化”时代,第三产业对经济的支撑作用持续增强。促进产业结构调整升级成为“十四五”期间我国经济发展的基本思路和政策走向。 HR 、 MS 、 OP 系数为正,即人力资本水平、金融发展程度、对外开放程度的提高能够促进全要素生产率的提升。 UR 系数为负,表明城市化水平对全要素生产率表现为抑制作用,因此城市化水平并非越高越好,城市化发展的“质”与“量”不协调可能会引发可持续发展。 FDI 与 OP 均不显著,说明外商直接投资和对外开放程度的影响不及其他要素^[16]。

2.3 影响规律分析

古典主动性决策理论认为,资源和其他客观存在的经

表4 各类要素对全要素生产率的影响效应

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$R\&D$	0.032*** (4.48)	0.022*** (4.60)	0.023*** (3.68)	0.026*** (3.34)	0.027*** (3.40)	0.026*** (3.31)	0.026*** (3.34)
RE	0.072*** (6.82)	0.026*** (3.36)	0.017* (1.76)	0.020* (1.71)	0.021* (1.78)	0.016 (1.25)	0.015 (1.21)
IND		-0.573*** (-17.74)	-0.499*** (-11.71)	-0.381*** (-6.32)	-0.373*** (-6.22)	-0.386*** (-6.32)	-0.372*** (-5.92)
HR			0.001** (2.50)	0.001 (0.17)	0.001* (1.91)	0.001 (1.34)	0.001 (1.40)
MS				0.001 (0.01)	0.001*** (3.38)	0.001*** (3.13)	0.001*** (3.23)
UR					-0.002* (-1.81)	-0.001 (-0.82)	-0.001 (-0.92)
OP						0.001 (1.11)	0.001 (1.07)
FDI							-0.001 (-1.04)
Cons	0.003 (0.04)	0.628*** (9.95)	0.607*** (7.90)	0.416*** (4.43)	0.503*** (4.81)	0.495*** (4.73)	0.499*** (4.77)
N	288	288	208	135	135	135	135
R^2	42.23%	73.53%	71.16%	75.82%	76.48%	76.72%	76.94%

注:括号内为t值。

济量为“形”,“形”发挥效能的条件和程度为“势”,量化体现为势效系数。势分析理论的精髓是在经济活动分析中,把资源发挥效能的程度和资源量本身放在同等重要的地位。因此,各类要素投入即为“形”,其对全要素生产率的影响程度体现为“势”。势效系数是一个随时间变化的时效函数,能够分析各要素发挥影响的动态规律。

根据势分析原理,定义势效系数如下:

$$r_{it} = \frac{\bar{X}_{it} * Y_{it} - \beta_0}{X_{it} * \bar{Y}_{it} - \beta_0} \quad (5)$$

式(5)中, r_{it} 为势效系数, X_{it} 为要素投入, Y_{it} 为要素产出, β_0 为截距项。

结合我国2001—2018年的实际数据,计算影响我国全要素生产率关键要素的势效系数,如下页表5所示。2001—2018年,我国各要素的势效系数总体呈上升趋势,说明在各要素的持续投入下资源得到更充分有效的利用,

对全要素生产率的影响效果不断提升,反映了投入产出的动态平衡。其中,IND 势效系数的提升速度和幅度最高,其次为 RE、UR、MS、R&D。这表明第三产业比重持续提高,其主导作用会进一步显现,第三产业超越第二产业成为我国经济增长的主动力已成为发展常态,促进我国经济向高质量的服务主导型转变;科技经费和人力投入并驾齐驱,对全要素生产率发挥了稳定持续的提升作用;在“质”与“量”协调的前提下,城市化依旧是重要驱动因素;人力资本的影响呈现波动态势,符合人力资本积累的长期性、不确定性特征。

表5 2001—2018年我国各要素的势效系数

年份	R&D	RE	IND	HR	MS	UR
2001	0.902	0.558	0.488	1.488	0.630	0.676
2002	0.870	0.598	0.570	1.252	0.664	0.708
2003	0.889	0.642	0.626	1.107	0.680	0.741
2004	0.886	0.687	0.678	1.045	0.753	0.773
2005	0.887	0.720	0.709	1.044	0.805	0.807
2006	0.912	0.765	0.739	1.060	0.831	0.841
2007	0.975	0.804	0.750	1.121	0.940	0.876
2008	0.993	0.849	0.811	1.192	1.011	0.912
2009	0.922	0.952	0.872	1.174	0.919	0.948
2010	0.956	1.009	0.914	1.162	0.975	0.984
2011	0.980	1.063	0.978	1.168	1.048	1.021
2012	0.970	1.120	1.024	1.109	1.075	1.060
2013	0.986	1.181	1.167	1.043	1.106	1.098
2014	1.028	1.248	1.313	0.845	1.146	1.137
2015	1.069	1.310	1.480	0.824	1.145	1.176
2016	1.101	1.376	1.632	0.834	1.178	1.216
2017	1.147	1.447	1.820	0.861	1.281	1.255
2018	1.185	1.510	1.946	0.879	1.393	1.295

3 结论与启示

与世界主要创新型国家相比,我国全要素生产率仍有进步空间,但逐年提升的改善趋势已经显现,与创新型国家平均水平的相对差距稳步缩小。不同要素对我国全要素生产率的影响效应与规律存在差异性、层级性:科技经费投入和第三产业发展对全要素生产率的提升作用最明显,科技人力投入、人力资本水平、金融发展程度亦具有提升效应。城市化水平则表现出抑制作用。并且,产业结构的影响效果最强,科技经费与人力投入对我国全要素生产率的提升发挥了稳定持续的作用。我国要素投入总体呈现资源利用率提高的趋势特征,体现出投入产出动态平衡的良性发展态势。

依据研究结论,本文得到如下启示:第一,正确理解全要素生产率的科学内涵,深刻认识我国现阶段提高全要素生产率的战略意义,充分遵循不同要素对全要素生产率的影响规律,构建与我国高质量发展形势相适应的全要素生

产率指标体系,有的放矢地推动全要素生产率的稳步提升。第二,对于我国而言,目前提高全要素生产率的关键环节是科学技术进步和优化资源配置,应着力优化科技经费投入结构,进一步加大自主研发力度,夯实基础研究能力,加快科技成果向现实生产力高质量转化。以产业结构转型升级为抓手优化资源配置,重视产业结构合理化与高级化的有机统一,实现产业结构调整平滑过渡,让第三产业成为拉动经济高质量发展的主引擎。

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政府和社会资本合作、区域经济协调发展与空间溢出

——基于空间杜宾模型的实证研究

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[摘要] 随着我国 PPP 步入规范发展的新阶段,推动经济高质量发展成为其转型升级的使命,准确评估 PPP 对区域经济协调发展的影响具有重要意义。文章采用空间杜宾模型实证检验 PPP 的空间效应,厘清行业异质性,进而考察双区制下地区间经济空间溢出效应的异质性。结果表明,PPP 不仅对邻近地区经济发展具有积极的溢出效应,而且能够提升经济发展的正向溢出效应,使本地区经济增长对邻近地区发挥出更强的辐射带动作用。交通运输领域应用 PPP 的经济效益最大,能源与水务领域具有正外部效益。

[关键词] 政府和社会资本合作;区域经济管理;空间效应

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一、引言

2020年7月,中共中央政治局会议作出“我国已进入高质量发展阶段”的重大判断。10月,党的十九届五中全会再次强调“推动形成优势互补、高质量发展的区域经济布局”。在开启全面建设社会主义现代化国家新征程的第一个五年,迈向新发展格局下更深层次的高质量发展、加快解决发展不平衡不充分问题有着更加重要的现实紧迫性。

一直以来,PPP作为项目投融资的创新模式、政企关系契约化与市场化的有效实践,在稳增长、补短板、促转型的背景下,得到了党中央和国务院的高度重视与鼓励支持,被广泛运用于基础设施和公共服务领域,逐渐成为供给侧结构性改革、混合所有制改革与行政管理体制改革中的重要力量。面临经济下行压力以及财政要过“紧日子”的形势,PPP或成为我国经济增长的新动能与区域协调发展的新机制。近年来,我国PPP项目规模保持了持续稳定的增长,截至2020年底,PPP管理库项目金额累计达到15.21万亿元¹。历经推广应用期、高速发展期、改革收紧期,我国PPP现已逐步回归理性,由重数量、重速度向重质量、重效率转变,迎来了全新的发展契机。2019年,国务院总理李克强在政府工作报告中提出要合理扩大有效投资,有序推进政府和社会资本合作,这是扩大

投资中首次提到PPP。3月,财政部发布的《关于推进政府和社会资本合作规范发展的实施意见》指出,充分发挥政府和社会资本合作的积极作用,提升公共服务的供给质量和效率,推动经济高质量发展。11月,国务院提出适当下调基建项目资本金比例,进一步撬动社会资本的“活力杠杆”。2020年11月,国家“十四五”规划纲要明确提出,支持区域协调发展的重大项目建设,更加注重发挥社会力量的作用。因此,在良好的政策前提下,在新发展格局的战略导向下,如何坚定不移地走好中国式PPP发展道路成为了至关重要的理论与实践命题。

那么,PPP的经济效果到底如何,其是否具有经济增长效应和空间溢出效应?不同行业的应用效果是否存在差异?它能否进一步改变经济发展的空间外溢?厘清这些关键问题,对于我国完善PPP顶层设计、优化PPP领域结构和布局、推动PPP为区域经济发展释放更强效能具有重要意义。本文的主要创新点在于:首次立足空间效应视角,研究PPP与经济发展的关系;基于双区制角度,验证PPP对经济发展空间外溢的影响;结合制度经济学理论,系统剖析PPP通过创新制度安排影响经济发展的作用机理。

二、文献回顾

关于PPP的经济后果,多数学者肯定了PPP与

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¹ 数据取自财政部社会资本合作中心“项目库信息公开”中“管理库项目金额”。

传统模式相比所具有的优势。经济价值上,PPP 通过增强财政政策与货币政策实施的有效性^[1],打破行政垄断、改善资源错配和提高全要素生产率^[2],提升了我国的经济发展水平,有效推动了我国实体经济的增长^[3],增加了社会福利^[4]。跨区域的研究表明,PPP 对“一带一路”沿线国家经济增长具有直接促进作用和间接溢出效应^[5]。治理价值上,PPP 不仅是融资模式的创新,更是公共管理模式和政府治理机制的创新^[6];一方面,PPP 使得公私双方通过签订长期契约构建稳固的合作关系,有效缓解了政府与社会资本间的委托代理问题,有利于激发社会资本进行技术创新的热情^[7],从而实现降本提效^[8-9]。另一方面,PPP 通过将市场机制有效引入公共领域,提高公共服务供给质量和效率,促进公共投资提效升级^[10-12]。

关于区域经济发展的动因,现有研究主要从投资规模、资本类型、基础设施等方面展开。其中,以投资为视角的研究又划分了政府投资、民间投资、行业投资、公共投资等不同维度。刘希章等^[13]研究表明,政府投资与民间投资均能促进经济增长,且民间投资具有正向的空间溢出效应。张方和陈凯^[14]指出,公共投资与本地区经济呈正相关关系,而与邻近地区呈负相关关系。陈乘风和许培源^[15]发现,社会资本具有通过技术创新提升经济绩效的链式关系。我国社会资本的作用在日益增强,地理边界更加明显,表现出一定的“引力”^[16],但其也有可能成为区域经济发展的障碍^[17]。基础设施的完善整体上促进了区域经济增长^[18-19],但呈现出边际效应递减的规律^[20]。

综上所述,现有研究已取得丰富成果,但仍存在深耕空间。一方面,尚未有实证研究从空间效应视角证实 PPP 与经济发展的关系。另一方面,相比其他投资,PPP 不仅具有投融资的经济效益属性,还具有公共服务的社会效益属性,以及政府和社会资本的合作伙伴属性。最后,多数研究未探讨不同区制下经济发展的空间外溢是否存在差异以及可能的动因。因此,除了验证 PPP 的经济增长效应,本文进而从空间效应、行业异质性、经济空间溢出效应异质性等三个视角,全面考察 PPP 对区域经济发展的影响。

三、理论分析

经济发展的空间依赖性 PPP 产生空间效应的重要前提^[21]。本文从制度创新、市场配置、契约协同、载体功能等四个视角剖释 PPP 对经济发展的内在作用机理。

(一)制度创新视角

根据制度经济学理论,有效的制度安排是促进经济增长的关键。制度创新是指创新主体为获取利益

对现有制度的变革^[22],包括诱导性、强制性两种形式,其中诱导性制度创新是在各类群体利益相容的情形下,通过一丝一扣的变迁逐渐累积达到帕累托最优改进。制度创新的有效性表现在通过协调各类群体的利益分配关系,使某些群体的利益增加而又不损害其他群体,促成各利益群体对改革达成共识,带来改革红利效应,促进经济发展^[23]。

PPP 的本质是充分发挥政府和社会资本各自的禀赋优势,进行相互合作的一项制度安排,对其理解应上升至以提升制度效率为核心的体制机制层面。首先,我国 PPP 的改革历程与制度经济学的逻辑进程是一致的。伴随我国经济社会的转型,以政府为单一主体开展投资、建设与运营的“行政垄断”制度安排形式难以继,暴露出财政资金短缺、供给能力不足、资源配置低效等种种弊端。此时,PPP 作为由政府发起的“循序渐进式”的诱导性制度创新,既使得政府的公共服务职能得以更好实现,又为社会资本提供了盈利与履行社会责任的机会,还通过充分发挥各方优势为社会公众带来更多物美价廉的产品和服务,最终达成政府、资本、民生“三赢”的帕累托最优改进^[24]。此外,诱导性制度创新的改革成本较低,引起的社会动荡较小,地方政府的介入使得“渐进式”改革能够平稳向好推进^[25]。

PPP 兼顾效率与公平,深度契合制度创新的核心内涵,通过持续推进供给侧结构性改革,提高经济发展质量和效益;其亦体现了混合所有制改革“从产权性质着手”的政策导向以及投融资体制改革的实务创新。因此,PPP 作为公共服务领域中符合国家和社会利益的有效制度创新^[26],具有促进经济发展的制度性效益。

(二)市场配置视角

新政治经济学中,公共产品理论是正确处理政府与市场关系、政府职能转变、公共服务市场化的基础理论。该理论认为关乎国计民生的公共产品和服务,不能完全交由追求利润最大化的市场来提供,需要政府发挥强有力的宏观调控功能。福利经济学理论进一步指出,政府强有力的宏观调控应仅限于税收和补贴方面,实现市场资源配置最优化的任务应交由私人部门通过竞争来完成。PPP 作为“半组织、半市场”的混合型经济组织形式,在资源配置中发挥的积极作用得到了较为充分的理论支持,具体体现在提升资源配置效率和优化资源配置结构两个层面。

一方面,PPP 在公共领域中引入市场化运作机制,充分尊重市场在配置资源中的决定作用,让市场参与公共资源的分配和管理,能够避免由长期行政垄断导致地方政府“攫取之手”的弊端,降低其带来的主动创租和无意创租的回报^[27],有利于消除政府独家模

式的低效性^[28]。并且,PPP通过进一步明晰政府与市场的边界,助推政府转变职能,逐步减少越位行为,回归监管服务本职。基于不完全对称性的制度设计和安排,政府在市场准入、价格制定、绩效考核等方面能够发挥更强的监管实效,避免企业陷入仅注重直接效益的单纯管理主义偏向,正确引导社会资本“逐利性”下的自身激励效应与社会效益相衔接。因此,除了市场自身的高效配置,政府和社会资本的非理性行为也

得到了有效约束,基于资源的有限性与选择性,资源配置效率得以提升。另一方面,在政府调控与市场调节双重效能的有机结合下,竞争性市场机制将进一步引导地方政府的财政资源向其他民生领域和薄弱环节倾斜,并通过促进社会资本之间充分竞争,推进资源配置在民生领域、社会资本参与中的结构性调整,最终达成追求供给质量和效率的长期性供给模式^[29],实现社会多元主体共建共享意义上的综合绩效。

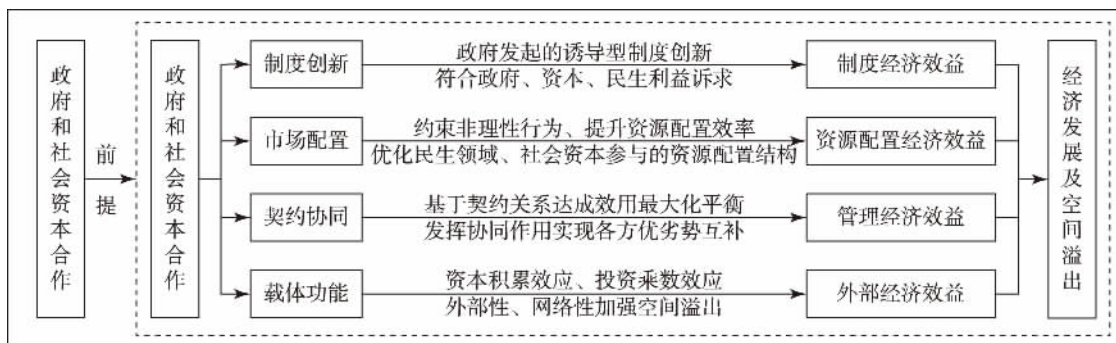


图1 PPP对经济发展的作用机理

（三）契约协同视角

世界银行将PPP定义为由私营部门同政府部门之间达成的提供公共资产和服务的长期合同。基于契约精神中的平等理念,政府和社会资本不应是上下级的隶属关系,而是平等的契约合作关系。因此,PPP是对政府与社会资本或对立或从属的传统关系的革命。在PPP项目中,政府和社会资本面临的并非是“囚徒困境式”的封闭信息环境,其决策磋商行为是在信息公开透明环境下的“讨价还价”,双方基于共识与信任的契约精神,通过合作博弈方式创造性地解决合作冲突、达成效用最大化的平衡。其次,根据委托代理理论,PPP能够通过契约和竞争有效缓解政府和社会资本间的信息不对称,有利于降低委托代理成本,化解逆向选择问题。

协同效应的经济学内涵最早被定义为“公司的整体效益大于各独立组成部分之和的经济效益”,即“ $1+1>2$ ”效应。在PPP项目中,协同的前提缘自政府和社会资本的优势互补^[30],地方政府具有强大的宏观调控能力以及抗风险能力,并且能够实施有力的政策引导;而社会资本具有的知识技能、管理经验、创新能力等“附加值”,在合作的催化之下往往更具效率。此外,PPP能够引入专业机构参与开发、实施与管理,形成政府、社会资本和专业机构“ $1+1+1>3$ ”的绩效提升机制^[31]。在中国特色的制度背景下,介于政府垄断和纯市场提供之间的PPP更能发挥出协同效应,将社会力量充分融入到推进基本公共服务均等化从而实现区域协调发展的重要路径。

（四）载体功能视角

除了发挥制度和市场“无形之手”,PPP本身作为

政府和社会资本的共同投资,具有天然的资本积累效应,从而促进经济发展。根据投资乘数理论,PPP能够带动全社会的投资,从而拉动就业与消费;还能够提升基础设施与公共服务的供给规模与质量,为业态创新、产业集聚“建平台”“搭梯子”。并且,伴随PPP理论与实践的不断完善,开发性PPP将成为融合新旧基建投入、产业导入与升级的新载体,旨在培育区域价值创造新机制,是我国区域协调开发与组织形式的又一次重大创新。

此外,得益于基础设施与公共服务的自身功能属性,PPP能够进一步促进地区经济发展及空间溢出。基础设施具有外部性和网络性特征,尤其是交通运输基础设施,显著地促进了劳动力、资本和技术等要素在不同区域之间流动^[32],通过投资效应和知识溢出效应带动区域经济协调发展^[33];而公共服务支出的提高促进了产业集聚,并且受偏好的影响存在外部性^[34]。PPP还能提升基础设施的经济产出效率^[35-37],从而进一步提高基础设施所带来的直接与间接经济效益。

四、研究设计

（一）样本选择

本文选择2003至2018年中国大陆31个省、自治区和直辖市作为研究样本。PPP数据来源于世界银行PPI数据库、财政部政府和社会资本合作中心,均为在库且执行的项目数据,剔除了中止、退库数据,同时鉴于通信行业的高度垄断性且在研究期内政府和社会资本合作较少,也予以剔除。经济发展数据来

源于 2004—2019 年《中国统计年鉴》,以及各地区《国民经济和社会发展统计公报》。市场化指数取自王小鲁等^[38]编制的《市场化指数报告》。

(二) 变量选取

本文选取 GDP 作为被解释变量。选取 PPP 项目总额作为解释变量,反映政府和社会资本合作。参照现有研究^[39-41],将各地区的财政自给率、财政负担率、对外依存度、市场化程度、人力资本、人口规模作为控制变量。其中,财政自给率是地方财政收入与财政支出的比值,衡量地区财政自力更生程度;财政负担率是地方财政收入与 GDP 的比值,综合反映政府与微观经济主体之间占有和支配社会资源的关系,衡量政府调控经济运行的能力和影响社会资源配置的程度。人力资本存量按照研究的一般做法,采用平均受教育年限来衡量,即按照不同的受教育程度赋予不同的权重进行加权平均。各变量的具体含义与描述性统计见表 1。

(三) 模型设定

本文首先考察 PPP 对本地区经济发展的影响,验证 PPP 的经济增长效应。因此,在不考虑空间相关性的情况下,构建 PPP 与经济发展的传统模型如下。

$$GDP_{it} = \alpha_0 + \alpha_1 PPP_{it} + \alpha_2 SU_{it} + \alpha_3 BU_{it} + \alpha_4 OP_{it} + \alpha_5 MI_{it} + \alpha_6 CP_{it} + \alpha_7 PO_{it} + \gamma_i + \delta_t + \mu_{it} \quad (1)$$

式(1)中, i 代表地区, t 代表年份; γ 和 δ 分别表示地区与年份固定效应。

传统模型中没有考虑空间效应,可能会导致模型设定存在偏误,进而使得参数估计有偏。Griffith^[42]提出引入空间权重矩阵,考虑变量之间潜在的空间相互依赖性,将传统研究视角引申至空间视域。空间权重矩阵包括邻接矩阵、距离矩阵和经济矩阵三种常见形式,邻接矩阵表示地区相邻关系,距离矩阵表示地理远近关系,经济矩阵则表示经济发展水平差异。本文使用距离矩阵来反映地区之间的空间关联性,空间权重矩阵中的元素定义为两地区地理经纬度距离平方的倒数。在式(1)的基础上引入距离矩阵,构建单区制空间面板杜宾模型(SDM)如下。

表 1 变量含义与描述性统计

变量	含义与计算	观测值	平均值	标准差	最小值	最大值
GDP	国内生产总值(取对数)	496	9.135	1.164	5.218	11.485
AGDP	人均国内生产总值(取对数)	496	10.262	0.738	8.190	11.851
PPP	PPP 项目总额(取对数)	496	3.420	2.619	0	9.403
SU	财政自给率(地方财政收入与支出之比)	496	0.498	0.203	0.056	0.951
BU	财政负担率(地方财政收入与 GDP 之比)	496	0.098	0.033	0.044	0.227
OP	对外依存度(进出口总额与 GDP 之比)	496	0.045	0.055	0.003	0.259
MI	市场化指数(取自研究报告)	496	6.255	2.068	-0.230	11.710
CP	人力资本(平均受教育年限)	496	10.685	1.450	4.524	15.184
PO	人口密度(人口数量与土地面积之比)	496	5.280	1.480	0.788	8.250

$$GDP_{it} = \rho \sum_{j=1}^N W_{ij} * GDP_{jt} + \alpha_1 PPP_{it} + \sum \alpha_k Control_{it} + \beta_1 \sum_{j=1}^N W_{ij} * PPP_{jt} + \sum \beta_k \sum_{j=1}^N W_{ij} * Control_{jt} + \gamma_i + \delta_t + \mu_{it} \quad (2)$$

式(2)中, ρ 为空间滞后系数,反映经济的空间依赖性; $Control_{it}$ 表示控制变量的集合; W_{ij} 表示 $N * N$ 维空间距离权重矩阵 W 中的各个元素; α 和 β 分别度量了各类因素对本地区与邻近地区经济发展的影响,其中 β 更能说明空间传导效应。

上述模型仅考虑了单一的空间依赖机制,无法反映不同区制下经济空间溢出效应的异质性。借鉴 Allers 和 Elhorst^[43]、Elhorst 和 Freret^[44]提出的双区制空间杜宾模型,本文在模型(2)的基础上,以有、无 PPP 作为分区标志,将单区制模型拓展至双区制情形,研究地区间经济空间溢出效应的差异,模型构建如下。

$$GDP_{it} = \rho_{D=1} d_{it} \sum_{j=1}^N W_{ij} * GDP_{jt} + \rho_{D=0} (1 - d_{it}) \sum_{j=1}^N W_{ij} * GDP_{jt} + \alpha_1 PPP_{it} + \sum \alpha_k Control_{it} + \beta_1 \sum_{j=1}^N W_{ij} * PPP_{jt} + \sum \beta_k \sum_{j=1}^N W_{ij} * Control_{jt} + \gamma_i + \delta_t + \mu_{it} \quad (3)$$

式(3)中,GDP 的空间滞后项被虚拟变量 d_{it} 划分为两个区制,有 PPP 时 d_{it} 取 1,否则取 0。 $\rho_{D=1}$ 和 $\rho_{D=0}$ 分别代表有、无 PPP 情形下地区经济的空间溢出效应,二者之差的大小和显著性反映地区处于不同状态时经济空间溢出效应的差异及其程度,是进一步判断 PPP 是否构成区域经济发展动因的重要依据。

五、实证分析

(一) 基本检验

1. 经济发展的空间自相关性

空间自相关分析常用的度量指标是 Moran's I 指数。本文分别计算 GDP、AGDP 各年的 Moran's I 指数(见表 2)来考察地区经济发展的空间自相关性。Moran's I 指数的取值范围为 $[-1, 1]$,大于 0 表示空间正相关,小于 0 表示空间负相关,且绝对值越大,空间相关性越强,说明本地区经济发展与邻近地区经济发展的相互依赖程度越高,表现为显著的空间集聚效应。

表 2 经济发展的 Moran's I 指数

年份	GDP		AGDP	
	Moran's I	Z	Moran's I	Z
2003	0.205***	2.628	0.412***	4.916
2004	0.204***	2.619	0.411***	4.906
2005	0.195**	2.532	0.421***	4.974
2006	0.191**	2.487	0.418***	4.933
2007	0.189**	2.458	0.411***	4.855
2008	0.188**	2.453	0.409***	4.811
2009	0.195**	2.534	0.385***	4.549
2010	0.193**	2.529	0.392***	4.609
2011	0.191**	2.506	0.377***	4.434
2012	0.188**	2.475	0.368***	4.333
2013	0.186**	2.455	0.359***	4.230
2014	0.187**	2.460	0.341***	4.036
2015	0.195**	2.545	0.329***	3.913
2016	0.205***	2.650	0.329***	3.918
2017	0.215***	2.759	0.343***	4.080
2018	0.213***	2.733	0.343***	4.083

*,**,***分别表示 10%,5%,1%的显著性水平。

由表 2 可知,2003—2018 年,GDP 和 AGDP 的 Moran's I 指数均大于 0,且至少通过了 5%的显著性检验,说明各地区经济发展表现为显著的正向空间依赖关系。图 2 直观地反映了各地区经济发展的空间分布趋势,一方面能够看出这种分布形式是非随机的,总体表现出高与高、低与低的分布形态,说明各地区的经济发展存在一定程度的“空间效仿性”。另一方面,多数地区集中于第一、第三象限,表明地区经济发展具有明显的空间集聚特征。上述结果符合我国的经济规律和实际,为本文研究视角的选定提供了支持,说明有必要从空间视域来探究经济发展的动因。

2. PPP 的经济增长效应

首先,运用传统模型(1)检验 PPP 对本地区经济发展的影响,厘清影响地区经济发展的各类因素及其效果。回归结果见表 3。

表 3 PPP 的经济增长效应

解释变量	被解释变量:GDP						
	1	2	3	4	5	6	7
PPP	0.005** (2.36)	0.004** (2.06)	0.004** (2.25)	0.004** (2.31)	0.004** (2.44)	0.004** (2.34)	0.003* (1.86)
SU		1.239*** (9.83)	1.474*** (10.48)	1.485*** (10.52)	1.443*** (10.40)	1.470*** (10.72)	1.530*** (11.05)
BU			-1.668*** (-3.59)	-1.708*** (-3.66)	-1.318*** (-2.83)	-1.463*** (-3.17)	-1.262*** (-2.71)
OP				-0.274 (-0.89)	-0.227 (-0.75)	-0.250 (-0.84)	-0.595* (-1.82)
MI					0.040*** (4.33)	0.045*** (4.83)	0.045*** (4.85)
CP						0.047*** (3.64)	0.050*** (3.86)
PO							-0.261** (-2.47)
Year	Control	Control	Control	Control	Control	Control	Control
Region	Control	Control	Control	Control	Control	Control	Control
R ²	97.82%	98.21%	98.26%	98.26%	98.33%	98.38%	98.40%
N	496	496	496	496	496	496	496

括号内为 t 统计值;*表示 10%的显著性水平;**表示 5%的显著性水平;***表示 1%的显著性水平;结果由 Stata14.0 得到;下同。

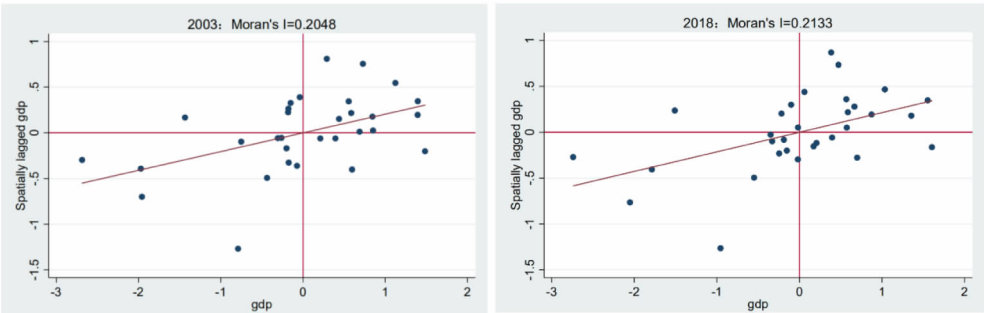


图 2 2003 年和 2018 年 GDP 的 Moran's I 散点图

由表 3 可见, PPP 与 GDP 始终存在显著的正相关关系, 说明政府和社会资本合作具有经济增长效应。SU 与 BU 分别从支出能力与收入水平角度反映了一个地区的财政实力, 其中 SU 的系数始终显著为正, 而 BU 的系数始终显著为负。由于中国采取财政分税制度, 中央政府会通过“财政转移支付”来平衡各地发展, 财政自给率高说明地方对中央的依赖度小、创造经济贡献的能力强。有别于财政自给率, 财政负担率必须控制在合理的范围之内, 过高说明政府集中的社会资源与财力过度, 不利于激发市场活力, 从而会削弱经济发展的基础。CP 的系数显著为正而 PO 显著为负, 说明经济发展的动力是人口素质的提高而非人口数量的增长。此外, 地区市场化程度的提高能够促进经济发展; 对外依存度与经济发展具有负相关关系, 说明经济发展的动能是依靠内需而非进出口驱动, 切合新发展格局下“以国内大循环为主体”的理论内涵。

3. PPP 的空间效应

基于全样本数据, 运用模型(2)检验 PPP 对经济发展的空间效应, 并进一步考察其他因素对邻近地区经济发展的影响。回归结果见表 4。

表 4 PPP 的空间效应

解释变量	被解释变量: GDP				
	影响系数		分解效应		
	本地区	邻近地区	直接效应	间接效应	总效应
PPP	0.003*	0.007*	0.004**	0.017**	0.020**
	(1.70)	(1.84)	(2.09)	(2.19)	(2.36)
SU	1.541***	-0.600*	1.565***	0.509	2.074***
	(12.60)	(-1.84)	(12.47)	(0.83)	(3.12)
BU	-1.669***	1.962*	-1.498***	2.220	0.723
	(-4.06)	(1.69)	(-3.55)	(0.94)	(0.28)
OP	-0.706**	1.207*	-0.617**	1.634	1.017
	(-2.46)	(1.94)	(-2.01)	(1.24)	(0.68)
MI	0.052***	-0.055**	0.049***	-0.053	-0.004
	(6.42)	(-2.13)	(5.93)	(-0.95)	(-0.07)
CP	0.026**	0.070**	0.036***	0.168**	0.205***
	(2.29)	(2.15)	(3.01)	(2.53)	(2.84)
PO	-0.207*	0.165	-0.204*	0.106	-0.098
	(-1.82)	(0.72)	(-1.84)	(0.25)	(-0.23)
ρ	0.536***				
	(8.92)				
σ^2	0.005				
Year	Control				
Region	Control				
R^2	76.53%				
LogL	603.844				
N	496				

表 4 中, ρ 为 0.536 且显著为正, 说明本地区经济发展对邻近地区具有显著的正向溢出效应。从影响系数来看, 各类因素对本地区经济发展的影响与表 3 一致。邻近地区系数中, PPP 显著为正说明本地区开

展政府和社会资本合作对邻近地区经济发展产生了正向的传导作用; CP 依旧显著为正, 表明本地区人力资本水平的提升对邻近地区经济发展亦具有积极影响; PO 不再显著, 说明人口规模并不具有空间传导作用, 符合客观实际。

相比影响系数, 分解效应能够更加准确的度量各类因素的影响程度。直接效应反映因素变化对本地区经济发展的影响程度, 间接效应反映对邻近地区的影响程度, 而总效应度量总体影响程度。本文重点解释直接效应和间接效应, 直接效应下各类因素的系数显著程度最高, 间接效应则大多不显著, 说明本地区经济发展主要依靠自身带动, 邻近地区所贡献的外溢效益是有限的。间接效应中仅有 PPP 和 CP 依旧显著且均为正, 说明 PPP、人力资本具有更明显的正向空间溢出效应。

(二) 异质性检验

本文从行业异质性的视角进一步考察 PPP 对经济发展的影响。回归结果见表 5。

区分行业后发现, 地区经济发展的空间溢出效应依然显著为正, PPP 对经济发展的影响存在明显的行业异质性。其中, 交通 PPP 在直接效应、间接效应和总效应上均显著为正, 说明政府和社会资本在交通运输领域合作的经济效益最大。原因在于, 交通作为区域经济一体化发展的大动脉, 是促进区域之间要素流动、提高经济运行质量和效率的重要基础, 调动社会资本与政府结成伙伴关系共建现代化交通运输治理格局是保障高质量发展的大势所趋。交通运输具有更强的外部性和网络性, 能够更好地发挥积极协同作用与空间溢出效应^[21,45]。能源与水务 PPP 直接效应不显著而间接效应显著, 说明其具有正外部效益^[46]。

(三) 拓展性检验

1. PPP 双区制下经济空间溢出效应的异质性

上述研究基于单区制情形考察了 PPP 的经济增长效应与空间效应, 并区分行业作了细化研究, 但尚未验证 PPP 对经济发展空间外溢的影响。进而, 本文以是否开展政府和社会资本合作作为分区标志将样本划分为两部分, 运用模型(3)进行检验。回归结果见表 6, 双区制下无法进行效应分解, 故只列示影响系数。由表 6 可知, 双区制模型的 R^2 达到了 99.64%, 拟合效果明显优于单区制模型的 76.53%。政府和社会资本合作状态下 GDP 的空间滞后系数为 0.786, 未合作状态下为 0.463, 均通过了 1% 的显著性检验, 系数差异为 0.323, 在 5% 的水平下显著, 说明 PPP 双区制下地区经济发展的空间溢出效应存在显著异质性, 即开展政府和社会资本合作的地区, 其经济发展对邻近地区的正向溢出效应明显高于未开展区域, PPP 能够提升本地区经济发展对邻近地区的辐射带动作用。

表 5 PPP 的行业异质性

解释变量	被解释变量:GDP								
	交通			能源			水务		
	直接效应	间接效应	总效应	直接效应	间接效应	总效应	直接效应	间接效应	总效应
PPP	0.004**	0.016*	0.020**	0.002	0.018**	0.020**	0.002	0.022*	0.024*
	(2.22)	(1.77)	(2.02)	(0.91)	(2.07)	(2.07)	(0.91)	(1.93)	(1.93)
SU	1.552***	0.498	2.050***	1.577***	0.621	2.198***	1.575***	0.504	2.079***
	(12.36)	(0.81)	(3.07)	(12.52)	(0.99)	(3.23)	(12.54)	(0.81)	(3.09)
BU	-1.547***	1.991	0.444	-1.505***	1.595	0.090	-1.609***	1.660	0.051
	(-3.65)	(0.84)	(0.17)	(-3.55)	(0.66)	(0.03)	(-3.76)	(0.69)	(0.02)
OP	-0.649**	1.559	0.910	-0.606**	1.831	1.225	-0.628**	1.469	0.841
	(-2.11)	(1.18)	(0.61)	(-1.97)	(1.35)	(0.80)	(-2.04)	(1.10)	(0.56)
MI	0.047***	-0.063	-0.016	0.050***	-0.050	-0.001	0.048***	-0.064	-0.016
	(5.65)	(-1.10)	(-0.26)	(6.01)	(-0.88)	(-0.01)	(5.69)	(-1.11)	(-0.27)
CP	0.039***	0.185***	0.224***	0.038***	0.186***	0.224***	0.038***	0.179***	0.217***
	(3.26)	(2.78)	(3.12)	(3.12)	(2.76)	(3.07)	(3.12)	(2.66)	(2.97)
PO	-0.215**	0.026	-0.190	-0.212*	0.041	-0.171	-0.233**	0.105	-0.128
	(-1.96)	(0.06)	(-0.45)	(-1.92)	(0.10)	(-0.40)	(-2.15)	(0.24)	(-0.29)
ρ	0.538***			0.545***			0.541***		
	(8.95)			(9.16)			(9.03)		
σ^2	0.005			0.005			0.005		
Year	Control			Control			Control		
Region	Control			Control			Control		
R^2	76.82%			72.21%			74.82%		
LogL	603.615			603.103			602.763		
N	496			496			496		

表 6 PPP 双区制下经济空间溢出效应的异质性

解释变量	被解释变量:GDP	
	影响系数(本地区)	影响系数(邻近地区)
PPP	0.004*	0.007*
	(1.66)	(1.78)
SU	1.538***	-0.568*
	(12.63)	(-1.74)
BU	-1.693***	1.870
	(-4.15)	(1.62)
OP	-0.752***	1.207*
	(-2.62)	(1.94)
MI	0.052***	-0.050*
	(6.40)	(-1.93)
CP	0.025**	0.083***
	(2.19)	(2.57)
PO	-0.198*	0.134
	(-1.74)	(0.59)
ρ_1	0.786***	
	(7.60)	
ρ_2	0.463***	
	(7.10)	
$\rho_1 - \rho_2$	0.323**	
	(2.49)	
σ^2	0.005	
Year	Control	
Region	Control	
R^2	99.64%	
LogL	605.181	
N	496	

2. PPP 双区制下的组间差异检验

为验证地区间经济空间溢出效应的异质性特征是否与地区自身的属性特征相吻合,对各个变量在两组中的均值差异进行显著性检验。结果见表 7。

表 7 PPP 双区制下的变量组间差异

变量	平均值		组间差异	
	有 PPP	无 PPP	差异	t 值
GDP	8.636	8.555	0.080	0.61
SU	0.545	0.454	0.091***	3.32
BU	0.078	0.110	-0.033***	-7.67
OP	0.051	0.051	0	-0.03
MI	6.843	5.621	1.223***	4.61
CP	10.109	10.615	-0.505**	-2.36
PO	5.542	4.841	0.701***	3.42

总体而言,PPP 双区制下两区表现出明显的结构性差异。其中,SU、MI、PO 的组间均值差异显著为正,说明经济空间溢出效应更强的地区,表现出市场化水平更高、财政自给能力更强、人口密度更大的属性特征,二者具有高度契合性。其次,王卓君等^[47]指出,市场化进程对于地方政府选用 PPP 具有促进作用;刘畅等^[48]指出,财政分权下财政自由度提升会促使地方政府选择 PPP。而人口密度更大可能意味着对公共服务规模与质量的需求更高,从而也会影响 PPP 的选用。因此,PPP 对地区经济发展正向溢出效应的提升作用与地区自身属性特征相吻合,研究结论的准确性在一定程度上得到印证。

[参考文献]

六、结论与建议

(一) 结论

本文重点研究了 PPP 对区域经济协调发展的影响。结果表明,PPP 不仅促进了本地区经济发展,还为邻近地区创造了正向的外部效益,并进一步发挥协同作用,提升了本地区经济发展对邻近地区的正向溢出效应,显现出我国持续推动 PPP 改革带来的红利效应。PPP 的影响存在明显的行业异质性,交通运输领域合作对本地区和邻近地区经济发展均具有促进作用,能源与水务领域合作具有正外部效益。在考察的各类动因中,人力资本与 PPP 对经济发展表现出更明显的正向空间溢出效应。

本文的研究既是对 PPP 经济后果的评估,又是将其置入区域经济发展动因的探讨,拓宽了现有文献的研究视角并作了重要补充,为我国有的放矢地完善 PPP 政策与制度环境,发挥 PPP 在交通运输领域的相对比较优势,引导 PPP 助推区域一体化融合发展提供了理论依据和参考。

(二) 建议

1.在加快建设交通强国的战略背景下,坚持因地制宜、按需而设、适度超前,加快谋划一批强基础、增功能、利长远的重大交通项目建设,打造区域综合交通大网络,发挥政府投资撬动作用,激发社会资本活力,形成市场主导的投资内生增长机制,让 PPP 为“交通基础设施互联互通”释放出更大效能,形成网络效应和整合效应,持续夯实区域更高质量一体化发展的载体基础。

2.继续深化投融资体制改革。一方面,要促进政府和社会资本合作结构多元化,运用好民营企业创新、运营等先天优势,鼓励民营企业以多种联合体形式参与 PPP 项目,推动国有企业、民营企业、外商投资企业融合发展与合作共赢,充分发挥不同类型企业的比较优势。另一方面,加强政信能力建设,强化政策保障,优化营商环境,为社会资本参与 PPP 项目创造更加公平、规范、开放的市场条件。

3.以区域协调发展为导向完善 PPP 顶层设计,培育 PPP 新型价值体系。立足国内经济大循环,完善区域政策和空间布局,统筹谋划 PPP 融入区域联动发展大格局,推广以区域可持续发展为目标的开发性 PPP,进一步出台支持政策,推动政府和社会资本建立长期合作关系,实现区域内公共服务与产业培育、新型城镇化相融合的一体化综合开发,促进区域产业和基础设施全面发展,持续提升区域“自我造血”功能,为区域发展创造增量价值,最终形成“公共服务—产城融合—财政增长—公共服务”的价值闭环。□

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基于多时期 DID 的高速铁路对城市人口流动的影响研究 *

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摘要: 高速铁路的迅速发展缩短了时空距离, 加速了人口、资源等经济要素的流动。基于 2004—2016 年我国 284 个地级及以上城市的数据, 运用多时期 DID 估计方法, 实证检验我国高速铁路对城市人口流动的影响。研究结果表明: ①总体上高速铁路对我国城市人口流动的影响呈现显著正向效应, 表现为人口集聚作用; 高速铁路成网的人口集聚作用相较于高速铁路开通更强。②不同人口规模下高速铁路对我国城市人口流动的影响存在显著的异质性。③高速铁路开通与成网对同一人口规模下城市的影响效果存在差异。

关键词: 高速铁路; 人口流动; 多时期 DID; 实证研究; 效应系数

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Research on the Impact of High-speed Railway on Urban Population Mobility Based on Multiple Periods DID

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Abstract: The rapid development of high-speed railway has shortened the distance between time and space and accelerated the flow of population, resources and other economic factors. Based on the data of 284 cities at the prefecture level or above in China from 2004 to 2016, this paper uses the multiple periods DID (Difference In Difference) estimation method to empirically test the impact of China's high-speed railway on urban population mobility. The research results show that: (1) On the whole, high-speed railway has a significant positive effect on urban population mobility in China, which is manifested as population agglomeration; The population agglomeration effect of high-speed railway network is stronger than that of high-speed railway opening; (2) The influence of high-speed railway on urban population mobility in China is remarkably heterogeneous under different population scale; (3) There are differences in the impact effects of high-speed railway opening and network completion on cities with the same population size.

Key words: high-speed railway; population mobility; multiple periods DID; empirical analysis; effect coefficient

0 引言

高速铁路的迅速发展显著改变了各项资源要素的空间布局, 提升了各项资源要素区域流动的速度与规模, 对城市人口流动产生了重要影响。高速铁路对城市人口流动的影响已成为学界研究的热点。部分研究表明高速铁路能够通过时空收敛效应引导人口和产业的集聚趋势^[1-3], 但也有研究表明高速铁路能够通过站点的扩散能力加快城市人口向周边地区或城市转移, 降低城市人口^[4-6]。这表明学界关于高速铁路人口效应的研究尚未形成统一结

论^[7], 有必要进一步研究。从现有研究看, 研究对象上, 已有文献更多侧重于检验高速铁路开通对城市人口流动的影响, 忽视了高速铁路成网作用于原有效应效果的影响探究; 研究方法上, 大多数学者采用的双期 DID 方法规定所有城市高速铁路开通于同一年份, 与实际不符, 可能导致结论有失精确。基于此, 以高速铁路开通、成网作为外生事件, 检验高速铁路对城市人口流动的总效应与异质性效应, 在模型设计方面对传统两期 DID 模型进行优化, 采用多期 DID 估计方法提高解释信度。

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1 高速铁路对城市人口流动的影响模型构建、检验流程及变量选取

1.1 多时期DID 模型

双重差分(Differences In Differences, DID)是用于评估政策实施效应的一项常用技术,在国内外许多研究领域得到了广泛的应用。标准的两期双重差分模型涉及一项政策或者事件发生的前后两期,即要求该事件或政策具有统一的发生时间,并以发生时间作为时间点分隔,进行前后两期比较,从而测度外生事件、政策冲击带来的效果。据此,将高速铁路开通、成网分别视为一次外生的近乎准自然实验,但由于各个城市高速铁路的开通与成网时间有先有后,设置统一时间点或者采用固定两期的方法难免有失准确性,因此借鉴 Beck 的做法^[8],在标准模型的基础上构建更加灵活的多时期 DID 模型,允许各城市有不同的政策实施年份。模型设立如下。

$$Lnpop_{ct} = \alpha + \beta HSR_{ct} + \delta X_{ct} + A_c + B_t + \varepsilon_{ct} \quad (1)$$

$$c=1, 2, \dots, 284; t=2004, 2005, \dots, 2016$$

式中: $Lnpop_{ct}$ 为城市 c 在年份 t 的人口规模; A_c 和 B_t 分别为城市和年份虚拟变量,表示城市固定效应与年份固定效应; HSR_{ct} 为核心解释变量(虚拟变量),其表示处理组且在政策发生后取 1,即城市 c 若在 t 时开通了高速铁路(高速铁路成网)则取 1,未开通(未成网)则取 0,该变量的取值设置来源于两期模型中的高速铁路开通(成网)虚拟变量与时间虚拟变量的交乘项,计算后很容易看出二者在两期条件下是等价的; X_{ct} 表示随着城市、时间不同而改变的、可能对被解释变量产生影响的控制变量的集合;系数 β 度量了高速铁路开通(成网)对城市人口规模的净效应。

1.2 检验流程

运用多时期 DID 模型对高速铁路对城市人口流动影响进行实证检验时,流程如下:首先,运用全样本数据建立多时期 DID 模型,区分高速铁路开通和成网两种情形,分别引入相关控制变量,观察系数 β 的显著性,对高速铁路对城市人口流动影响的总体效应进行基本检验。其次,将样本城市按照人口规模分组回归,区分高速铁路开通和成网两种情形,就不同组别的高速铁路对城市人口流动影响的效应进行对比分析,开展异质性检验。最后,为验证上述结果的稳健性,对被解释变量进行替换,进行稳健性检验。

1.3 变量选取

1) 被解释变量。由于地级市的常住人口数据无法取得,因此选取年平均人口数作为研究的被解释变量。与时点人口指标相比,年平均人口数作为人口统计指标中常用的时期性指标,缓解了人口流动极端化趋势对人口规模的影响,能够更综合、平稳地反映一个城市全年的人口规模。同时,为了保证结果的稳健性,选用人口密度进行替代检验。

2) 解释变量。核心解释变量为高速铁路开通虚拟变量和高速铁路成网虚拟变量,分别反映高速铁路开通、成网对城市人口流动的影响。

3) 控制变量。关于人口流动的影响因素,研究表明经济发展水平是影响人口流动的主要因素^[9-11]。此外,还选择产业结构、职工工资水平、公共服务水平等作为控制变量。

变量含义及计算方法如表 1 所示。本文选取 2004—2016 年我国 284 个地级及以上城市作为研究样本,数据主要来源于 2005—2017 年《中国城市统计年鉴》。

表 1 变量含义及计算方法

变量类型	变量名称	变量含义	计算方法	单位	预期符号
被解释变量	$lnpop_1$	人口规模	年平均人口的对数	万人	
	$lnpop_2$		人口密度的对数	人/km ²	
解释变量	HSR_1	高速铁路开通	开通取 1;未开通取 0		+/-
	HSR_2	高速铁路成网	成网取 1;未成网取 0		+/-
控制变量	$RGDP$	经济发展水平	平减后 GDP(实际 GDP)的对数	万元	+
	AW	收入水平	职工工资总额/从业人员数	万元	+
	MSR	产业结构	第二产业比重/第三产业比重		-
	$Road$	城市道路	年末实有道路面积的对数	万 m ²	+
	$Hospital$	医疗卫生	医院和卫生院数量的对数	个	+
	$Fiscal$	公共资源	政府财政支出的对数	万元	+
	RI	住房条件	政府住宅投资的对数	万元	+



2 高速铁路对城市人口流动影响的实证检验

2.1 基本检验

高速铁路对城市人口流动影响的总体效应全样本回归结果(高速铁路开通)如表 2 所示。从表 2 可以看出,在未加入任何控制变量的情况下,高速铁路开通效应系数显著为正;逐个加入控制变量后,该项系数仍然正向显著,且稳定在 0.012 的水平,表明高速铁路开通对城市人口流动具有正向效

应,表现为人口集聚作用。观察控制变量的系数及显著性后,GDP、职工平均工资、政府财政支出、医院及卫生院数及住宅投资在置信度 99%的水平下始终显著为正,说明城市的经济发展水平、收入水平、资源投入、医疗卫生条件、住房水平对城市人口流动有显著正向影响,同时 GDP 的系数始终保持最大,反映出城市经济发展水平是影响城市人口流动的核心因素,与现有学者研究一致;产业结构的

表 2 全样本回归结果(高速铁路开通)

被解释变量:年平均人口($\ln pop_1$)								
解释变量	1	2	3	4	5	6	7	8
HSR_1	0.012 2*** (6.07)	0.013 7*** (6.91)	0.012 7*** (6.45)	0.012 7*** (6.47)	0.012 7*** (6.47)	0.012 4*** (6.37)	0.012 8*** (6.55)	0.012 9*** (6.65)
$RGDP$		0.045 5*** (10.22)	0.037 8*** (8.42)	0.046 4*** (9.25)	0.046 2*** (9.16)	0.045 1*** (8.97)	0.038 7*** (7.22)	0.036 7*** (6.81)
AW			0.013 5*** (8.72)	0.012 6*** (8.02)	0.012 6*** (8.02)	0.012 8*** (8.20)	0.013 1*** (8.40)	0.013 6*** (8.65)
MSR				-0.005 9*** (-3.80)	-0.006 0*** (-3.81)	-0.006 1*** (-3.86)	-0.006 7*** (-4.22)	-0.006 5*** (-4.12)
$Road$					0.000 7 (0.33)	0.001 2 (0.59)	0.000 9 (0.41)	0.000 4 (0.17)
$Hospital$						0.009 6*** (5.20)	0.009 5*** (5.22)	0.009 3*** (5.12)
$Fiscal$							0.013 6*** (3.43)	0.011 6*** (2.90)
RI								0.004 3*** (3.29)
N	3 692	3 692	3 692	3 692	3 692	3 692	3 692	3 692
R^2	0.444 6	0.461 2	0.473 0	0.475 2	0.475 3	0.479 5	0.481 3	0.483 0

注:①括号内的数值为 t 值;②***,**, * 分别表示在 1%,5%,10%的统计水平上显著;③估计结果由 Stata12.0 计算得出。

系数始终显著为负,说明第二产业比例增加、第三产业比例降低对城市人口流动产生了负向影响,第二产业对人口的吸纳程度不及第三产业。城市道路系数虽不显著但为正,说明其对城市人口集聚的影响不明显。以上结果与预期一致,符合我国经济发展的一般规律。

全样本回归结果(高速铁路成网)如表 3 所示。从表 3 可以看出,在未加入任何控制变量的情况

下,高速铁路成网效应系数显著为正;逐个加入控制变量后,该项系数仍然正向显著,且稳定在 0.021 的水平。与高速铁路开通效应系数相比,高速铁路成网效应系数更大,说明高速铁路成网对城市人口流动的正向效应、人口集聚作用更强。控制变量的系数符号及显著性水平与高速铁路开通全样本回归的结果保持一致。

表 3 全样本回归结果(高速铁路成网)

被解释变量:年平均人口($\ln pop_i$)								
解释变量	1	2	3	4	5	6	7	8
HSR_2	0.028 9*** (7.66)	0.027 7*** (7.45)	0.020 5*** (5.35)	0.021 3*** (5.57)	0.021 3*** (5.58)	0.020 6*** (5.40)	0.021 1*** (5.53)	0.021 3** (5.59)
$R GDP$		0.042 2*** (9.50)	0.035 8*** (7.99)	0.045 0*** (8.98)	0.044 7*** (8.87)	0.043 7*** (8.69)	0.037 4*** (6.98)	0.035 4*** (6.58)
AW			0.012 0*** (7.44)	0.010 8*** (6.67)	0.010 8*** (6.66)	0.011 1*** (6.87)	0.011 4*** (7.04)	0.011 8*** (7.27)
MSR				-0.006 4*** (-4.06)	-0.006 5*** (-4.08)	-0.006 5*** (-4.11)	-0.007 1*** (-4.46)	-0.006 9*** (-4.37)
$Road$					0.001 0 (0.46)	0.001 6 (0.71)	0.001 2 (0.54)	0.000 7 (0.31)
$Hospital$						0.009 5*** (5.20)	0.009 4*** (5.15)	0.009 2*** (5.05)
$Fiscal$							0.013 2*** (3.31)	0.011 2*** (2.80)
RI								0.004 2*** (3.20)
N	3 692	3 692	3 692	3 692	3 692	3 692	3 692	3 692
R^2	0.448 1	0.462 4	0.471 0	0.473 6	0.473 6	0.477 8	0.479 5	0.481 0

注:①括号内的数值为 t 值;②***, **, * 分别表示在 1%, 5%, 10% 的统计水平上显著;③估计结果由 Stata12.0 计算得出。

2.2 异质性检验

现有研究表明,城市类型对高速铁路人口效应的发挥具有重要影响,因此,将样本城市按照人口规模进行分组以考察高速铁路对城市人口流动的异质性效应。

人口规模的分组标志参照 2014 年 11 月国务院发布的《国务院关于调整城市规模划分标准的通知》:城市规模按照人口数量划分为 5 类 7 档,即超大城市(1 000 万人以上)、特大城市(500 万~1 000 万人)、I 型大城市(300 万~500 万人)、II 型大城市(100 万~300 万人)、中等城市(50 万~100 万人)、I 型小城市(20 万~50 万人)、II 型小城市(20 万人以下);研究采用 2014 年各城市年末人口数作为划分依据。由于人口数量在 20 万以下的城市样本量不

足,故将 I 型小城市(20 万~50 万人)与 II 型小城市(20 万人以下)合并为“小城市”(50 万人以下)。

基于人口规模的分组回归(高速铁路开通)如表 4 所示。不同人口规模下城市高速铁路开通效应系数如图 1 所示。回归结果显示,高速铁路开通对城市人口流动的影响因城市人口规模的不同而存在显著的异质性。无论是否加入控制变量,高速铁路开通系数在不同分组下的回归结果都显著,其中超大城市系数显著为负,其余显著为正;系数大小随城市人口规模的降低而增加,以上说明高速铁路开通对城市人口流动的影响效果随城市人口规模的降低而增强,高速铁路对中小城市的人口集聚作用相比大城市明显更强,对超大城市则表现为人口扩散作用。

表 4 基于人口规模的分组回归(高速铁路开通)

被解释变量:年平均人口($\ln pop_i$)														
变量	超大城市		特大城市		I 型大城市		II 型大城市		中等城市		小城市		中小城市	
HSR_1	-0.008 5*** (-1.97)	-0.000 7*** (-0.14)	0.004 5*** (2.02)	0.007 7*** (0.72)	0.011 7*** (2.90)	0.010 5*** (2.71)	0.018 0*** (4.85)	0.022 6*** (6.36)	0.058 1*** (3.62)	0.027 (1.55)	0.158 4*** (3.55)	0.112 9*** (2.39)	0.076 6*** (4.67)	0.063 7*** (3.97)
$R GDP$	-0.039 5** (-2.10)		0.034 9*** (4.13)		0.015 7*** (1.39)		0.035 4*** (4.50)		0.135 6*** (3.49)		0.190 6*** (2.14)		0.091 8*** (2.94)	
AW	-0.003 2 (-0.95)		-0.006 2*** (-2.94)		0.024 4*** (6.55)		0.019 9*** (7.21)		0.020 5 (1.39)		0.028 5 (1.52)		0.015 6* (1.67)	



续表

被解释变量:年平均人口($\ln pop_1$)														
变量	超大城市		特大城市		I 型大城市		II 型大城市		中等城市		小城市		中小城市	
MSR	0.023 0** (2.56)		-0.001 0*** (-3.14)		-0.017 7*** (-4.36)		-0.007 4*** (-2.93)		-0.009 7 (-0.96)		0.002 1 (0.15)		-0.004 6 (-0.89)	
$Road$	-0.009 9 (-1.11)		0.003 2 (1.22)		-0.008 8** (-2.04)		0.000 1 (0.02)		0.008 3 (0.39)		-0.306 8 (-1.54)		0.000 5 (0.02)	
$Hospital$	-0.003 (-0.18)		-0.007 9*** (-2.61)		0.015 2*** (3.35)		0.000 8 (0.32)		0.079 4** (2.51)		0.058 4 (2.81)		0.055 8*** (4.74)	
$Fiscal$	-0.031 3 (1.60)		0.000 9 (0.19)		0.014 6 (1.63)		0.016 5*** (2.67)		-0.041 7 (-1.23)		-0.105 6 (-1.26)		-0.090 8*** (-3.40)	
RI	-0.002 3 (-0.40)		0.008 7*** (4.39)		-0.002 7 (-0.93)		0.004 5** (2.39)		0.005 3 (0.69)		0.024 1 (0.86)		0.011 4 (1.62)	
N	169	169	1 157	1 157	1 001	1 001	1 222	1 222	104	104	39	39	143	143
R^2	0.892 1	0.903 2	0.715 8	0.730 4	0.388 3	0.446 5	0.343 7	0.416 5	0.484 7	0.676 0	0.713 4	0.845 3	0.502 6	0.673 3

注:①括号内的数值为 *t* 值;②***, **, * 分别表示在 1%, 5%, 10% 的统计水平上显著;③估计结果由 Stata12.0 计算得出。

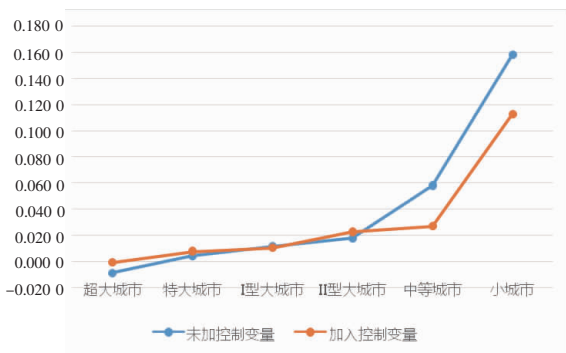


图 1 不同人口规模下城市高速铁路开通效应系数

基于人口规模的分组回归(高速铁路成网)如表 5 所示,不同人口规模下城市高速铁路成网效应系数如图 2 所示。由于中小城市样本量不足,高速铁路成网效应只度量大城市的 3 种细分类别(将超大城市与特大城市合并)。结果表明,除 II 型大城市

系数为负且不显著,其余显著为正,说明高速铁路成网效应也存在显著的异质性,其对 I 型大城市表现为显著的人口集聚作用且效应最强,对于 II 型大城市则表现为显著的人口扩散作用,对于超大和特大城市表现为人口集聚作用但效果并不显著。

表 5 基于人口规模的分组回归(高速铁路成网)

被解释变量: 年平均人口 ($\ln pop_1$)										
变量	超大及特大城市		超大城市		特大城市		I 型大城市		II 型大城市	
HSR_2	0.084 4** (2.81)	0.014 3*** (4.50)	-0.001 9*** (-0.40)	0.008 7 (1.51)	0.007 8** (2.18)	0.013 3*** (3.67)	0.071 6*** (9.26)	0.062 7*** (8.26)	-0.010 0 (-0.64)	-0.019 6 (-1.32)
$RGDP$		0.015 2** (2.00)		-0.041 3** (-2.26)		0.032 2*** (3.83)		0.015 3 (1.41)		0.031 4*** (3.93)
AW		0.003 3* (-1.89)		-0.005 (-1.43)		-0.007 3*** (-3.41)		0.020 1*** (5.49)		0.019 4*** (6.91)
MSR		-0.008 1*** (-2.68)		-0.023 6*** (2.65)		-0.011 0*** (-3.47)		-0.016 8*** (-4.27)		-0.008 1*** (-3.61)
$Road$		0.000 6 (0.23)		-0.010 4 (-1.21)		0.002 9 (1.13)		-0.008 5** (-2.04)		0.000 7 (0.19)
$Hospital$		-0.005 9** (-2.01)		-0.001 1 (-0.07)		-0.007 9*** (-2.62)		0.013 4*** (3.06)		0.001 2 (0.47)

续表

变量	被解释变量:年平均人口($\ln pop_1$)									
	超大及特大城市		超大城市		特大城市		I型大城市		II型大城市	
<i>Fiscal</i>	0.004 6 (0.98)		0.034 7* (1.84)		0.001 6 (0.33)		0.014 7* (1.70)		0.014 4** (2.29)	
<i>RI</i>	0.009 1*** (4.88)		-0.001 5 (-0.27)		0.008 6*** (4.36)		-0.004 9*** (-1.74)		0.004 6** (2.41)	
<i>N</i>	1 326	1 326	169	169	1 157	1 157	1 001	1 001	1 222	1 222
<i>R</i> ²	0.738 1	0.747 8	0.889 3	0.904 8	0.716 0	0.730 8	0.435 7	0.481 1	0.330 0	0.396 2

注:①括号内的数值为t值;②***, **, * 分别表示在1%,5%,10%的统计水平上显著;③估计结果由Stata12.0计算得出。

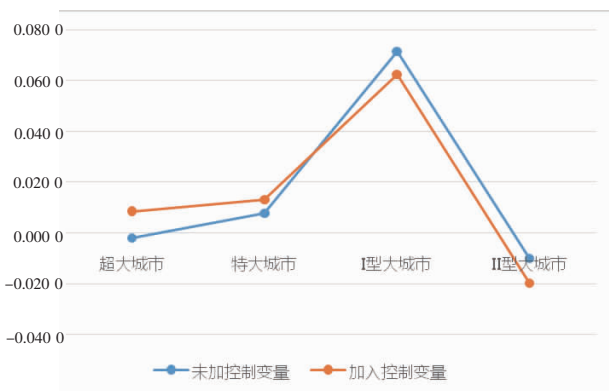


图2 不同人口规模下城市高速铁路成网效应系数

不同人口规模下城市高速铁路开通、成网效应系数比较如图3所示。根据图3可以看出,高速铁路开通与成网对同一人口规模下城市的影响效果也存在差异。II型大城市的高速铁路开通与成网效应相反,表明随着II型大城市高速铁路开通到成网,其人口表现为“先集聚后扩散”;I型大城市高速铁路成网显著增强了原本的人口集聚能力;而对超大城市、特大城市而言,前后效应水平相差不大。

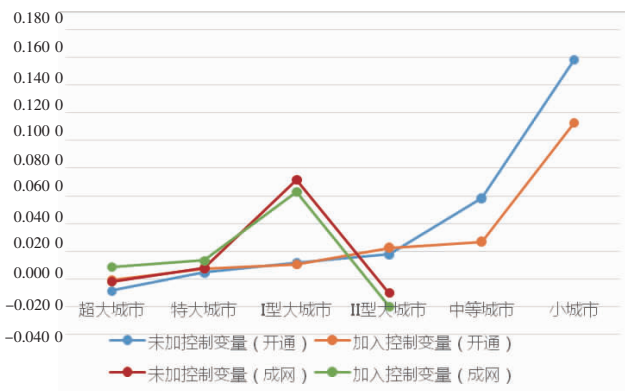


图3 不同人口规模下城市高速铁路开通、成网效应系数比较

2.3 稳健性检验

为了检验上述结果的稳健性,使用人口密度作为被解释变量对年平均人口进行替换,对其进行对数化处理以保证量级的一致性;并分别进行全样本回归、按人口规模的分组回归。结果表明,替换被解释变量后,全样本回归及按照人口规模分组回归的结果与上文基本保持一致,证明研究结果稳健。

3 研究结论

利用2004—2016年我国284个地级及以上城市的数据,运用多期DID模型实证分析高速铁路对城市人口流动的影响,得到以下基本结论。

1) 总体上,高速铁路对我国城市人口流动的影响呈现显著的正向效应,表现为人口集聚作用;高速铁路成网的人口集聚作用相较于高速铁路开通更强。

2) 不同人口规模下高速铁路对我国城市人口流动的影响存在显著的异质性。高速铁路开通对城市人口流动的影响效果随城市人口规模的降低而增强,其对中小城市的人口集聚作用相比大城市明显更强,对超大城市则表现为人口扩散作用;高速铁路成网对I型大城市表现为显著的人口集聚作用且效应最强,对于II型大城市则表现为显著的人口扩散作用,对于超大和特大城市表现为人口集聚作用但效果并不显著。

3) 高速铁路开通与成网对同一人口规模下城市的影响效果存在差异。II型大城市的高速铁路开通与成网效应相反,表明随着II型大城市高速铁路开通到成网,其人口表现为“先集聚后扩散”;I型大城市高速铁路成网显著增强了原本的人口集聚能力;而对超大城市、特大城市而言,前后效应水平相



差不多。

综合以上结论分析,可能的经济社会原因在于由于大城市的城市化水平高,自身人口规模已达近饱和水平,吸引人口集聚的城市空间明显不足,加之由于政策影响,大城市往往实施更为严格的落户制度,进一步限制人口向其流动。相比而言,我国中小城市的城市化水平有长足提升空间,近年来城镇化发展速度也明显加快,其就业、生活等方面压力较小,加之人口福利、就业政策等的实施,使中小城市日趋成为人们选择就业、居住的考虑方向;同时大城市的人口集聚对中小城市也会产生虹吸作用。

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(上接第7页)哈萨克斯坦运费较高的情况,协调建立各国之间运输费用的统一标准核算体系,并允许沿桥集装箱运输价格的市场化波动,借鉴西伯利亚大陆桥价格运作机制,形成更有竞争优势的运价水平。

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Research on the Investment Efficiency of Transport Infrastructure in Countries Along the Belt and Road



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Abstract Adopting Stochastic Frontier Analysis (SFA), we firstly estimate the investment efficiency of transport infrastructure in 20 countries along the Belt and Road from 2000 to 2017, and then we empirically examine the impacts of the public–private partnership (PPP) and the Belt and Road Initiative (BRI). The results show that, from 2000 to 2017, the average transport infrastructure investment efficiency of these 20 countries is 0.552, with different degrees of resource waste and efficiency loss, despite the improvement trend is sound. And the efficiency of the developed countries is higher. The results also manifest that the application of PPP, the increasing amount of and investments on PPP projects all significantly helped improve the efficiency, which implies a good effect of PPP. Moreover, the efficiency had been significantly improved since the BRI was put forward in 2013, which proves the value and effectiveness of this worldwide policy.

Keywords Stochastic frontier analysis (SFA) · Public–private partnership (PPP) · The belt and road initiative (BRI) · Transport infrastructure · Investment efficiency

1 Introduction

According to 2018 BMI's global infrastructure statistic data, the proportion of newly signed contracts of transportation ranked the highest among all industries in countries along the Belt and Road. And *The Belt and Road International Infrastructure Development Index Report* released in 2019 also claimed that the demand index for the development of transportation industry was higher than that of other industries, suggesting great investment and development opportunities regarding infrastructure connectivity for countries along the route.

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Projects on transport infrastructure typically anticipate rather massive investments, long recovery cycles, intensive funding and technological supports. As a consequence, the traditional investment mode with the government acting as the single agent is gradually insufficient to meet the demand for building up such infrastructure. As a worldwide popular financing mode for infrastructure, PPP has currently become mainstream in funding international cooperation of the BRI, and has been extensively applied into practice.

Can the promotion of the BRI improve the efficiency of investment? Is the application effect of PPP better than the traditional modes? Only few studies by far have concentrated on infrastructure investment efficiency by using quantitative analytical approaches. Zhongmin et al. [1] and Chenyang and Lianghai [2] measured and analyzed the transport infrastructure efficiency in countries along the Belt and Road adopting Data Envelopment Analysis (DEA). Juan et al. [3] investigated the economic growth brought by investments on road, railway and other infrastructure in countries along the and Road with a regression method. The empirical research of Dongfang [4] showed that the PPP investment was significantly positively correlated with the infrastructure efficiency. Lixin et al. [5] used the multi-period Differences-in-Differences method to assess the impact of PPP implementation on China's infrastructure output efficiency and found it causing no significant improvement. We can conclude that most scholars used DEA, a non-parameter estimation method based on linear programming to evaluate the infrastructure efficiency, so the accuracy of their results can be further enhanced. Also, few literatures have studied the relationship between PPP and the investment efficiency of infrastructure. Most of them took PPP only to be a policy shock while ignoring the impact of PPP projects' number and the scale of investments, so the comprehensiveness and robustness of their results needs to be improved.

In view of the above, we use a more precise SFA approach to estimate the investment efficiency of transport infrastructure in 20 countries along the Belt and Road from 2000 to 2017. In order to get more robust and accurate empirical results, we consider three dimensions of PPP, namely the implementation of PPP which is a dummy variable, the number of PPP projects and the investment amount. We are also interested in the policy effects of the BRI, so we add it to our regression and process it as a dummy variable. In addition, we further analyze the path and mechanism of the impact of PPP on the investment efficiency of infrastructure. On the whole, What we aim to explore is the effectiveness of the BRI policy, and our work is of practical significance to further refinement and promotion of PPP in the field of transport infrastructure.

2 SFA and Investment Efficiency Estimation

SFA and DEA are output efficiency measurement methods commonly used in economics. Unlike DEA, a non-parameter estimation method based on linear

programming, SFA construct production frontiers by utilizing the production function. It requires highly precise model setting and data, and can be flexibly adjusted according to the characteristics of the research object; it is also of high pertinency and accuracy in measurement, all of which make it suitable to process large samples. What is more, SFA takes the impact of random factors on output into consideration, which avoids DEA's insufficiency in attributing the output deviation all to technical efficiency, and can make the estimation result more reliable. Regarding these, we choose to employ SFA to estimate the investment efficiency of transport infrastructure.

2.1 Model Specification

Production functions commonly used for SFA are Cobb-Douglas function and Trans-Log function. The former is concise in form and the parameters are endowed with meanings directly from economics, but only under the premise that the returns to scale remain constant; while the latter overcomes this shortcoming by considering the impact of capital and labor interaction on output, making the parameter estimation more consistent with the economic facts.

According to the basic principles of the model constructed by Battese and Coelli [6], we use logarithmic C-D function to build the analytic model:

$$\text{Ln}Y_{it} = \beta_0 + \beta_1 \text{Ln}K_{it} + \beta_2 \text{Ln}L_{it} + v_{it} - u_{it} \quad (1)$$

Trans-Log function generalizes C-D function on the basis of formula (1):

$$\begin{aligned} \text{Ln}Y_{it} = & \beta_0 + \beta_1 \text{Ln}K_{it} + \beta_2 \text{Ln}L_{it} + \beta_3 t + 1/2\beta_4 (\text{Ln}K_{it})^2 \\ & + 1/2\beta_5 (\text{Ln}L_{it})^2 + 1/2\beta_6 t^2 + \beta_7 \text{Ln}K_{it} \text{Ln}L_{it} \\ & + \beta_8 t \text{Ln}K_{it} + \beta_9 t \text{Ln}L_{it} + v_{it} - u_{it} \end{aligned} \quad (2)$$

$$u_{it} = e^{-\eta(t-T)} u_i \quad (3)$$

In formula (1) and (2), Y_{it} represents output, K_{it} represents capital input, L_{it} represents labor input, β_1 represents capital output elasticity, β_2 represents labor output elasticity; The error term is a composite structure, in which v_{it} obeys Independently Identically Distribution and $u_{it} \geq 0$ obeys Half-Normal Distribution to represent the impact only on individual factor.

In formula (3), η is a time-varying parameter. $\eta > 0$ indicates an efficiency increase over time, and vice versa.

The technical efficiency is defined as:

$$TE_{it} = e^{-u_{it}} \quad (4)$$

If $u_{it} = 0, TE_{it} = 1$, indicating that the individual production scale is on the production frontier, suggesting a state of technical efficiency. If $u_{it} > 0, 0 < TE_{it} < 1$, the individual production scale is below the production frontier, suggesting a state of technical inefficiency.

As for the selection of the function form, a model based on the Trans-Log function is generally used to perform model setting test. Based on the statistical test result, combined with the nature of the research object and whether the parameter estimation results are consistent with common sense, etc., we can make a comprehensive judgment.

2.2 Indicator Selection

Considering data comparability and availability, the GDP of 20 countries along the Belt and Road are selected as output, the number of employees in transportation industry as labor input, and investments on transport infrastructure (including railway, road, water and air transport) as capital input. The data derives from the World Bank database, the OECD database and *Yearbook of China Transportation and Communications*.

2.3 Estimation Result

The infrastructure investment system is a multi-objective, multi-variable and non-linear input-output system. That the input-output increment multiplies from the original increment by a fixed ratio does not accord with the objective conditions in reality, and does not apply to the premise that the returns to scale are constant [7]. The result of our model setting test (see Table 1) also proves that the Trans-Log production function is more suitable.

Table 1 Result of model setting test

	Coefficient	Standard-error	T-ratio
σ^2	0.277	0.202	1.372
γ	0.935***	0.047	19.737
μ	0.194	0.419	0.464
η	0.043***	0.004	11.056
Log likelihood = 158.232***			
LR statistic = 648.369***			

Note (1) ***, **, * respectively indicate statistically significance of 99%, 95%, and 90%; (2) Only the core and relevant results are listed

$\gamma = 0.935$, indicates that there is an evident composite structure in the error term. So it is necessary to employ SFA instead of simple linear analysis. $\eta = 0.043$, shows that the investment efficiency of transport infrastructure in these 20 countries has been increasing year by year.

Table 2 presents the estimation of the investment efficiency based on the Trans-Log function.

The sample countries are grouped according to their degrees of development, and the average investment efficiency of each group is listed in Table 3.

The above results show that: (1) the investment efficiency of transport infrastructure in 20 countries along the Belt and Road does not reach the optimal production efficiency and manifests a technical inefficient state, although it has been increasing with each passing year; (2) the average investment efficiency of transport infrastructure in these countries is 0.552, and that of the developed countries is 0.722, which is much higher than 0.479 of the less-developed countries. But Turkey, as a developing country, reaches an average investment efficiency as high as 0.967. Its ranking first is inseparable from Turkey's policy of massive investment in infrastructure to fuel economic growth. At present, Turkey has become one of the most potential markets in emerging economies to attract foreign investments; (3) 90% of the countries below the average investment efficiency are less-developed, and the average investment efficiency of Moldova ranks in the last with 0.160, which is rooted in its lagging economy dominated by agriculture and animal husbandry, its frequent occurrence of political conflicts and economic crises.

3 Theory Analysis and Research Hypothesis

As a project financing mode, PPP has been widely used in the field of infrastructure construction and public management. Developed countries are still the main and mature PPP markets. According to the theory of public goods, transport infrastructure belongs to the quasi-public goods, with limited non-competitiveness and non-excludability. It can generate revenue and be provided by the market. Meanwhile, as the market is not constantly efficient in the allocation of resources, it requires the government to exert powerful macro-control functions. So this provides the basis for public-private partnership in the field of transport infrastructure.

Most studies have confirmed the superiority of PPP over the traditional supply mode. Guangliang et al. [8] pointed out that PPP can effectively introduce market mechanisms into the public domain and improve the efficiency of public services. PPP is not only an innovation of financing mode, but also of public management and administrative governance [9]. PPP has inherent advantages and can improve the quality and efficiency of public service supply [10]. Stulz [11] showed that PPP, being a "semi-organized, semi-market" hybrid way of organization, on the one hand can avoid the disadvantages caused by the local government's "grabbing hands" out of long-term administrative monopolies, therefore reducing the active rent creation

Table 2 Investment efficiency of transport infrastructure in 20 countries from 2000 to 2017

Country	Year																	
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Turkey	0.954	0.956	0.957	0.959	0.961	0.962	0.964	0.965	0.967	0.968	0.969	0.971	0.972	0.973	0.974	0.975	0.976	0.977
	0.918	0.921	0.924	0.927	0.930	0.933	0.936	0.938	0.941	0.943	0.945	0.947	0.950	0.952	0.954	0.955	0.957	0.959
Slovenija	0.720	0.730	0.740	0.749	0.758	0.767	0.775	0.784	0.792	0.799	0.807	0.814	0.821	0.828	0.834	0.841	0.847	0.853
Czech	0.712	0.722	0.732	0.742	0.751	0.760	0.769	0.777	0.785	0.793	0.801	0.808	0.815	0.822	0.829	0.836	0.842	0.848
Poland	0.680	0.691	0.701	0.712	0.722	0.732	0.741	0.751	0.760	0.768	0.777	0.785	0.793	0.801	0.808	0.815	0.822	0.829
Slovakia	0.587	0.600	0.613	0.626	0.638	0.650	0.662	0.673	0.685	0.696	0.706	0.716	0.726	0.736	0.746	0.755	0.764	0.772
Hungary	0.546	0.560	0.573	0.587	0.600	0.613	0.626	0.638	0.650	0.662	0.673	0.684	0.695	0.706	0.716	0.726	0.736	0.745
Croatia	0.513	0.527	0.542	0.556	0.569	0.583	0.596	0.609	0.622	0.634	0.646	0.658	0.670	0.681	0.692	0.703	0.713	0.723
Estonia	0.467	0.482	0.497	0.512	0.526	0.541	0.555	0.568	0.582	0.595	0.608	0.621	0.633	0.646	0.657	0.669	0.680	0.691
Russia	0.451	0.467	0.482	0.496	0.511	0.526	0.540	0.554	0.568	0.581	0.595	0.608	0.620	0.633	0.645	0.657	0.668	0.680
China	0.424	0.439	0.455	0.470	0.485	0.500	0.514	0.529	0.543	0.557	0.571	0.584	0.597	0.610	0.623	0.635	0.647	0.659
Lithuania	0.402	0.418	0.433	0.448	0.464	0.479	0.494	0.508	0.523	0.537	0.551	0.565	0.579	0.592	0.605	0.618	0.630	0.643
Latvia	0.366	0.381	0.397	0.413	0.428	0.444	0.459	0.474	0.489	0.504	0.518	0.533	0.547	0.561	0.574	0.588	0.601	0.614
Romania	0.286	0.301	0.316	0.332	0.347	0.363	0.379	0.394	0.410	0.425	0.441	0.456	0.471	0.486	0.501	0.516	0.530	0.544
India	0.262	0.277	0.292	0.307	0.323	0.338	0.354	0.370	0.385	0.401	0.416	0.432	0.447	0.463	0.478	0.493	0.507	0.522
Serbia	0.233	0.247	0.262	0.277	0.292	0.308	0.323	0.339	0.354	0.370	0.386	0.401	0.417	0.432	0.448	0.463	0.478	0.493
Bulgaria	0.210	0.224	0.238	0.253	0.268	0.283	0.298	0.314	0.329	0.345	0.361	0.376	0.392	0.407	0.423	0.438	0.454	0.469
Albania	0.112	0.123	0.134	0.146	0.158	0.171	0.184	0.197	0.211	0.225	0.240	0.254	0.269	0.284	0.300	0.315	0.331	0.346
Azerbaijan	0.112	0.123	0.134	0.146	0.158	0.171	0.184	0.197	0.211	0.225	0.240	0.254	0.269	0.284	0.300	0.315	0.331	0.346
Georgia	0.112	0.123	0.134	0.146	0.158	0.171	0.184	0.197	0.211	0.225	0.240	0.254	0.269	0.284	0.300	0.315	0.331	0.346
Moldova	0.068	0.076	0.085	0.094	0.104	0.114	0.125	0.136	0.148	0.160	0.173	0.186	0.200	0.213	0.228	0.242	0.257	0.272
(continued)																		

(continued)

Table 2 (continued)

Country	Year																	
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Average	0.451	0.463	0.475	0.488	0.500	0.512	0.524	0.536	0.548	0.559	0.571	0.583	0.594	0.606	0.617	0.628	0.639	0.649

Note The investment efficiency is sorted from high to low

Table 3 Average investment efficiency of transport infrastructure of each group

Type	Country	Average investment efficiency
Developed	Slovenija; Czech; Slovakia; Hungary; Estonia; Latvia	0.722
Less-developed	Turkey; Poland; Croatia; Russia; China; Lithuania; Romania; India; Serbia; Bulgaria; Albania; Azerbaijan; Georgia; Moldova	0.479

and unintentional effects. On the other hand, it is also able to make maximum use of social resources and increase social welfare [12].

From a macro point of view, PPP can enhance the degrees of marketization in the field of transport infrastructure, effectively releasing market vitality and stimulating the quality and efficiency of economic growth. At the micro level, PPP not only relieves the government’s financial pressure, but also takes full advantage of social capital’s rich management experience, advanced technology and complete information to reduce transaction costs. Moreover, the incentive effect caused by private profit-seeking will help to reduce the whole life cycle cost of PPP projects, improve the operational efficiency and service level, thus achieve a win-win result between economic and social benefits. In this light, we put forward the first research hypothesis:

H1: PPP can improve the investment efficiency of transport infrastructure.

Since the BRI was first proposed in 2013, this keynote initiative from China and belongs to the world has received numerous responses and praises. A total of 65 countries along the route have joined into this initiative, making it an global cooperation and exchanges of public goods with worldwide popularity.

Infrastructure connectivity is an important part of the BRI. It demands a massive amount of investments [13]. Meanwhile, the BRI has effectively solved a series of problems especially in the shortage of domestic capital supply in relevant countries, enabling them to enjoy the financial resources from other countries along the route as well as from the international market. Wei et al. [14] found that the openness level of these countries was generally on the rise, which effectively promoted the economic growth in the area. Yujuan [15] introduced the Belt and Road dummy variable into her research and pointed out that the BRI can boost the economic along the route and optimize China’s overseas investment structure. Accordingly, we put forward the second research hypothesis:

H2: The Belt and Road Initiative can improve the investment efficiency of transport infrastructure in countries along the route.

4 Empirical Test

4.1 Data, Variables and Model

1. Data. We select data of 20 member states of the BRI from 2000 to 2017 as research samples. PPP data of transport infrastructure derives from PPI database, and economic data derives from World Bank database. Individual missing data is supplemented by using linear interpolation.
2. Variables. The investment efficiency of transport infrastructure estimated by SFA is taken as the explained variable; PPP implementation, PPP projects number, PPP investment amount and the BRI are selected as explanatory variables. We also choose the levels of urbanization, financial development, the degrees of opening-up, industrial structure, as well as the economic growth of each country as control variables. The specific meaning and descriptive statistics of the above variables are presented in Table 4.
3. Model. According to the results gained from the Hausman test, we adopt the panel fixed effect model.

$$IE_{it} = \alpha_0 + \alpha_1 PPP_{nit} + \alpha_2 Control_{it} + \varepsilon_{it} \quad (5)$$

Table 4 Descriptive statistics of variables

Type	Name	Meaning	Mean	SD	Min	Max
Explained	<i>IE</i>	Transport infrastructure investment efficiency	0.552	0.234	0.068	0.977
Explanatory	<i>PPP</i> ₁	Transport infrastructure PPP implementation or not	0.225	0.418	0	1
	<i>PPP</i> ₂	Transport infrastructure PPP projects number	1.906	7.378	0	73.00
	<i>PPP</i> ₃	Transport infrastructure PPP investment (logarithm)	4.547	8.526	0	24.33
	<i>BRI</i>	The Belt and Road Initiative	0.222	0.416	0	1
Control	<i>MS</i>	Financial development: broad money/GDP	57.93	35.41	10.38	209.50
	<i>OP</i>	Opening-up: (import + export)/GDP	82.20	37.13	19.31	176.20
	<i>IND</i>	Industrial structure: secondary industry/tertiary industry	0.53	0.156	0.216	0.947
	<i>UR</i>	Urbanization: urban population/total population	58.54	11.40	27.67	74.67
	<i>EC</i>	Economic growth: growth rate of GDP per capita	4.562	4.605	-14.27	33.00

$$IE_{it} = \beta_0 + \beta_1 BPI_{it} + \beta_2 Control_{it} + \varepsilon_{it} \quad (6)$$

In formula (5) and (6), IE_{it} is the investment efficiency of transport infrastructure. There are three measurement methods for PPP_n : PPP_1 is a dummy variable for PPP implementation, values 1 for implementation and 0 for non-implementation; PPP_2 indicates the number of PPP projects; PPP_3 indicates the investment amount on PPP. BRI_{it} is a dummy variable for the Belt and Road Initiative. In 2013, the BRI was formally proposed by China, and therefore, 2013 is taken as the node before which BRI_{it} values 0 and after which values 1. $Control_{it}$ represents a collection of control variables. ε_{it} represents the error term. α_1 and β_1 respectively measure the net effect of PPP and the BRI on the investment efficiency of transport infrastructure.

4.2 Result and Analysis

First, we use model (5) to test the impact of PPP on the investment efficiency of transport infrastructure. The regression results are shown in Table 5.

PPP implementation, PPP projects number, and PPP investment are all significantly in positive correlations with the investment efficiency of transport infrastructure, which proves that the regression results is of high validity. It is indicated that PPP can improve the investment efficiency of transport infrastructure, in line with Hypothesis 1. *MS*, *OP*, and *UR* are constantly significantly positive with 99% confidence, indicating that the financial development, the degrees of opening-up, and the level of urbanization can promote the improvement of investment efficiency in transport infrastructure. *IND*'s and *EC*'s being negative suggests that the development of the service industry has improved the investment efficiency of transport infrastructure more than the secondary industry; and that the rapid economic growth will bring more unimpeded financing channels along with a sound institutional environment, partly reducing the spillover effect of PPP. The above results are generally consistent with our expectations and conform to the general law of world economic development.

Next, we use model (6) to test the impact of the BRI on the investment efficiency of transport infrastructure. The regression results are shown in Table 6.

With or without the control variables, the *BRI* coefficient is always significantly positive, indicating that there is a significant difference in the investment efficiency of transport infrastructure among the countries before and after the promotion of the BRI, that is, the investment efficiency remarkably improved after the countries entered the initiative, confirming that this policy is of profound value and effectiveness. The significance of the control variables are consistent with the above analysis, so there would not be further discussion.

Table 5 Regression results of PPP

Explained variable: IE									
Variable	1	2	Variable	3	4	Variable	5	6	
PPP ₁	0.0455*** (3.29)	0.0158** (1.99)	PPP ₂	0.0013* (1.84)	0.0008** (2.09)	PPP ₃	0.0025*** (3.45)	0.0008* (1.91)	
MS		0.0035*** (10.72)	MS		0.0035*** (10.63)	MS		0.0035*** (10.68)	
OP		0.0007*** (3.56)	OP		0.0007*** (3.28)	OP		0.0007*** (3.56)	
IND		-0.0917* (-1.77)	IND		-0.1315** (-2.53)	IND		-0.0958* (-1.86)	
UR		0.0038*** (3.32)	UR		0.0038*** (3.35)	UR		0.0038*** (3.28)	
EC		-0.0019*** (-3.01)	EC		-0.0017*** (-2.82)	EC		-0.0019*** (-3.02)	
Cons		0.0896 (1.30)	Cons		0.1165* (1.68)	Cons		0.0943 (1.37)	
R ²	3.10%	71.74%	R ²	0.99%	71.79%	R ²	3.39%	71.70%	

Note (1) The values in parentheses are *t* values; (2) ***, **, * respectively indicate statistically significance of 99%, 95%, and 90%; (3) the estimated results were processed by Stata14.0

Table 6 Regression results of the BRI

Explained variable: <i>IE</i>		
Variable	1	2
<i>BRI</i>	0.1039*** (16.71)	0.0459*** (7.85)
<i>MS</i>		0.0029*** (9.49)
<i>OP</i>		0.0006*** (3.15)
<i>IND</i>		−0.0469 (−1.01)
<i>UR</i>		0.0029*** (2.83)
<i>EC</i>		−0.0017*** (−3.06)
<i>Cons</i>		0.1556** (2.50)
<i>R</i> ²	45.17%	77.11%

5 Research Conclusion

1. From 2000 to 2017, the average investment efficiency of transport infrastructure in 20 countries along the Belt and Road is 0.552—far less than 1, the state of technical efficiency—which indicates that input and output of transport infrastructure is suffering from efficiency loss and resource waste, despite an overall rising trend. The average investment efficiency of the developed countries is 0.722, higher than 0.479 of the less-developed countries. Turkey, Slovenia, Czech Republic, Poland, Slovakia, and Hungary have relatively higher investment efficiencies with an average of 0.822, which is close to the optimal efficiency. 90% of the countries below the average investment efficiency are less-developed. The average investment efficiency of Moldova, ranking at the bottom with 0.160, has to do with the country's political turbulence and economical backwardness.
2. Both the implementation of PPP and the increasing number of and investments on PPP projects can enhance the investment efficiency of transport infrastructure, which proves that PPP, as a majorly market operation, enables the participation of social capital to balance the allocation of resources, to improve the resource efficiency, and to generate ample profits. It is worth noting that such a conclusion does not imply that we encourage unrestricted employment of PPP or as many investments as possible. The number of and investment on PPP projects reflect the construction volume and service scale of infrastructure just to a limited extent. Only by building more high quality PPP projects and determining reasonable

- project investment scale can the infrastructure investment efficiency be improved in the long range, forming favorable scale effects and positive external effects.
3. After the BRI was put forward, the investment efficiency of transport infrastructure in countries along the route has been significantly improved. The reasons are that, on the one hand, comprehensive infrastructure development and transport interconnectivity are two priorities of the initiative. Transportation is strategically crucial as it can lead further development of all industries, and therefore resulting in a huge demand of constructions and investments of the related countries. On the other hand, the BRI connects developed and developing economies and establishes an all-round financial cooperation system to break the bottleneck of funding, which extensively promotes the exchanges of and communications on advanced experience and technology. “Financial integration”, as is suggested by this initiative, has played an important role in funding and safeguarding infrastructure development as well as improving investment efficiency in the Belt and Road region.

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曾获重要荣誉

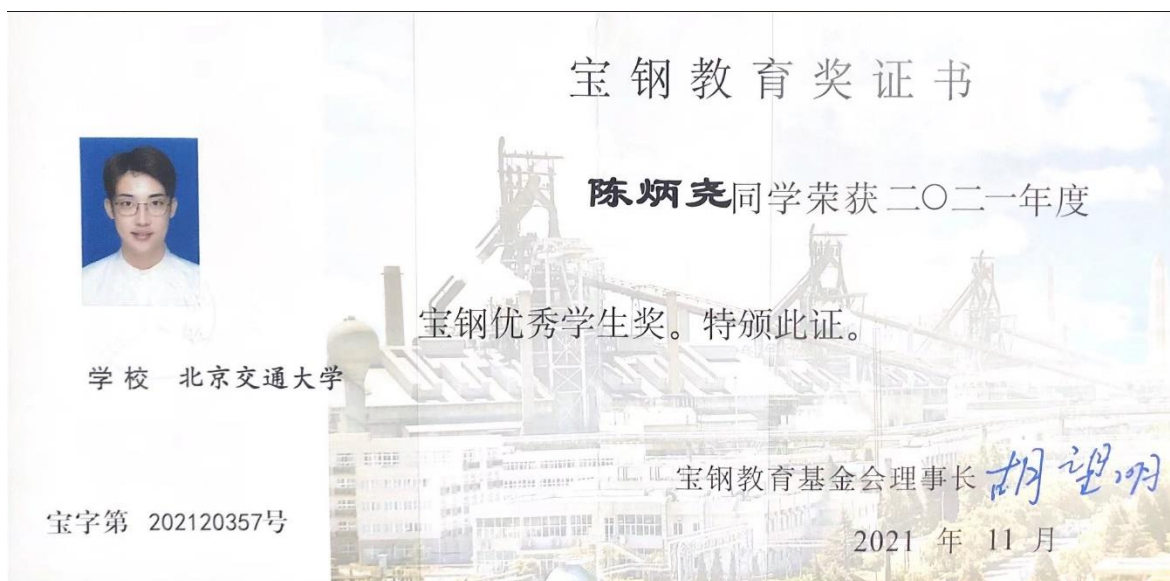
1. 知行奖学金（本科生）



2. 2021 至 2022 学年博士研究生国家奖学金和徐寿波院士奖学金 (国奖证书还未发放)



3. 2021 年度全国“宝钢优秀学生奖”及特等奖提名



关于北京交通大学2021年宝钢优秀学生奖推荐人选的公示

校内各单位：

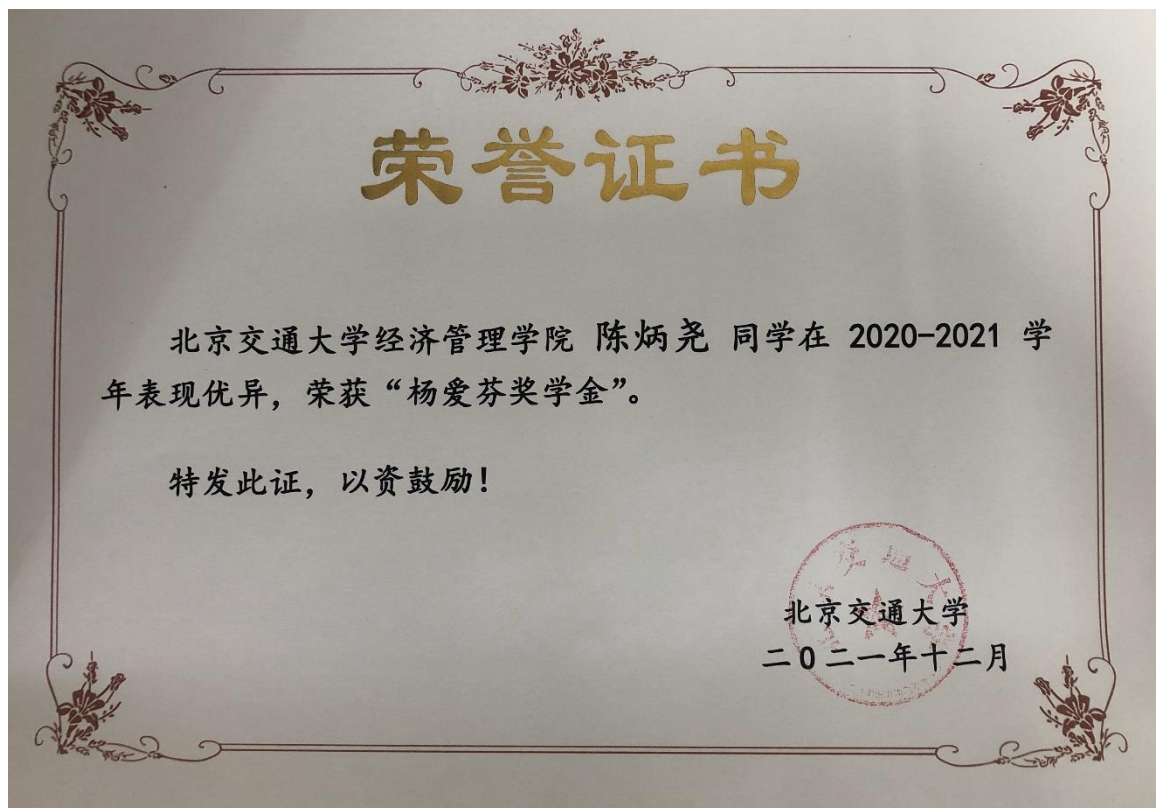
经各单位推荐、学校相关部处审查、学校宝钢教育奖评审领导小组评审、学校党委会常委会研究审定，确定北京交通大学2021年宝钢优秀学生奖推荐人选。现公示如下：

序号	学院	姓名	在读学历
1	电信学院	王奕润	本科
2	运输学院	范伟康	本科
3	经管学院	陈炳尧	博士
4	计算机学院	吕庚育	博士
5	机电学院	李禄权	博士

推荐经管学院陈炳尧为宝钢优秀学生特等奖提名人选

公示期为2021年9月22日至9月27日，如有异议，请以书面并署名的形式向教育基金会反映。

4. 2020 至 2021 学年“杨爱芬奖学金”



5. 2018 年“硕士研究生国家奖学金”



6. 2019 至 2020 年度“北京市优秀学生干部”



7. 2020 年度“首都大学生暑期社会实践先进个人”



青年服务国家

陈炳尧：

在2020年首都大中专学生暑期社会实践工作中表现突出、成绩显著、被评为“2020年度首都大中专学生暑期社会实践先进个人”。



二〇二〇年十二月



8. 国奖、北京市三好、首都优秀团员



陈炳尧 同学

荣获二〇一五年至二〇一六年度
北京市三好学生。特颁发此证。



二〇一七年三月

证书

陈炳尧 同学：

荣获二〇一六年至二〇一七年度
北京市优秀学生干部。特颁此证。



二〇一八年三月



社会工作、先进事迹等



共青团北京市第十四次代表大会代表



交通大学第二十四次学生代表大会



北京交通大学
学生会主席



共青团北京交通大学委员会

证 明

兹证明经济管理学院陈炳尧（学号：18113068），于2018至2019学年、2019至2020学年，任职北京交通大学学生会副秘书长，工作认真积极，圆满完成了交予的各项任务。

特此证明！



北京交通大学学生会副秘书长

聘 书

LETTER OF APPOINTMENT

兹聘请陈炳尧同学担任北京交通大学第三十一届研究生会执行主席，聘期为二〇一九年十二月至二〇二〇年十月。

此聘

北京交通大学党委
研究生工作部

共青团北京交通大学
委员会

北京交通大学
研究生会

二〇一九年十二月十日

北京交通大学研究生会主席

中国大学生骨干培养学校

第十一期拟录取学员公示

学 校	姓 名	院系专业
北京大学	王泰蒙	哲学
北京大学	秦 川	药学
北京大学	孙北奇	工学院
清华大学	祁诗皓	经济管理学院金融硕士
中国人民大学	李恒森	经济学院区域经济学
中国人民大学	王鸿铭	中国政治
北京师范大学	吕欣娜	教育学部教育学
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北京科技大学	李晓彤	冶金工程
北京交通大学	陈炳尧	经管学院会计学



中国大学生骨干培养学校学员

在身体力行中受教育、长才干、做贡献

201607-201608	全国大学生暑期社会实践赴山东青岛“发展蓝色经济”
201708-201709	全国大学生暑期社会实践赴江苏太仓“扶持小微企业”
201807-201808	全国大学生暑期社会实践赴泰国老挝“高铁走向国门”
202008-202009	全国大学生暑期社会实践赴陕西丹凤“助力脱贫攻坚”



全国百强团队

北京市百强团队

北京市社会实践优秀个人

校级社会实践先进个人





央视采访与宣传片拍摄



旁听外交部例行新闻发布会



受邀参加第一届中国青年发展论坛及青年博士智库成立大会



全国高校研究生学习论坛



环保宣传教育活动旗手、学生代表

学校开学典礼发言



经济管理学院2018级博士研究生陈炳尧代表在校生发言。他向新生分享了三点在交大求学七年的感悟，鼓励同学们找准定位、提高站位、知行合一、脚踏实地，用饱满的热情、踏实的行动、昂扬的斗志，书写靓丽的人生答卷。

学院迎新大会发言

经济管理学院召开2022级迎新大会

2022-09-05 16:32 信息来源：经管学院 6714



2022年9月4日下午，经济管理学院在天佑会堂召开2022级迎新大会。院党委书记李彤、院长施先亮、党委副书记张欣颖、党委副书记、副院长郭名、副院长周耀东、裴晓东、尚小博和学生工作办公室主任张云鹏、教师代表穆东、学生会执行主席廉懿阳、研究生会执行主席刘志伟在主席台就座。新生班主任、辅导员及一千三百余名新生们通过直播方式线上参加本次大会。大会由张欣颖主持。



在校生代表、2018级博士研究生陈炳尧同学代表老生发言，
级新生代表、经管2203班陆子航同学表达了对交大校园生活的

校友之家揭牌仪式发言及电子校友卡发布学生代表



校长王稼琼，副校长高艳，机电学院80级校友、北京农学院党委书记杨军，以及2018级博士研究生陈炳尧在会上共同发布电子校友卡。截至目前，共有六千余名校友注册了校友卡。





学校先进个人表彰大会



身边的榜样事迹报告会

报告嘉宾简介

陈炳尧



陈炳尧，男，北京交通大学经济管理学院2018级会计学直博生，学习成绩优异，曾三获国家奖学金，并荣获北京交通大学学生最高

“四所交大” 博士生论坛

“百年伟业，智能领航” 四所交大博士生论坛成功举办

为庆祝北京交通大学建校125周年，增进四所交大的兄弟情谊，促进交大学子共同进步，10月18日19:00，由北京交通大学发起主办，上海交通大学、西安交通大学、西南交通大学共同协办的四所交大博士生论坛在线上拉开帷幕。论坛邀请了四所交大的博士生代表，以“百年伟业，智能领航”为主题，开展学术论坛，为青年学子提供思想碰撞与交流的平台，展现交大学子的学术风范。



校研会郭晓蒙同学介绍了本次博士生论坛的举办背景、目的、意义以及对本次活动的展望，北京交通大学研究生工作部李兴友老师祝贺四所交大博士生论坛活动成功启动，感谢各兄弟院校研工部和团委等相关老师的大力支持，回忆了四所交大之间源远流长的情谊，表达了对四所交大博士生同学们学有所成的祝福与期待。



四所交大选派优秀博士生代表在本次论坛上进行了分享交流：来自北京交通大学经管学院的陈炳尧博士从“一个中心、两个能力、三个途径、四个维度”的角度出发，分享了他的博士期间学习和生活的经历，鼓励同学们在做好科研的同时积极参与社会实践、社会服务、志愿服务、创新创业，来自上海交通大学机械与动力工程

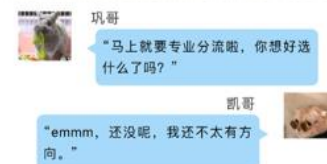


“学长学姐说”系列活动 | 第一期简报

热爱学习的 可爱的天佑1班大家庭 4月29日

收录于话题
#“学长学姐说”系列活动

1个 >



“詹天佑班” 经验分享与交流



研究生“英语文化节”戏剧类二等奖



大信杯MPAcc中心案例大赛三等奖



本科毕业晚会演唱嘉宾



学术会议与高水平实习等

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《国铁集团财务集中管控研究》课题前期准备工作情况汇报

前期准备工作情况汇报

按照公司党委书记、董事长徐志民同志关于做好《国铁集团财务集中管控研究》课题前期准备工作的要求，公司经管所、财务部在课题需求理解分析及研究方案建议的基础上，加强与国铁集团财务部进行需求对接，并赴太原开展实地调研、邀请专业机构进行培训，通过理论、实践层面的准备，我们深化了对本课题研究内容、重点问题的认识，为后续开展研究工作打下了坚实的基础。现汇报如下：

一、课题前期准备工作情况

针对财务部提出的课题研究要求，我们通过文献研究、实地调研、专家培训等方式，对本课题涉及的基本概念、方

1.1 课题背景及研究意义

随着国铁集团财务集中管控的深入推进，各铁路局集团公司财务集中管控工作面临诸多挑战。本课题旨在研究国铁集团财务集中管控的可行性和实施路径，为集团财务集中管控提供理论支持和实践指导。

1.2 课题研究目标

1. 明确国铁集团财务集中管控的内涵和外延。
2. 分析国铁集团财务集中管控的可行性和实施路径。
3. 提出国铁集团财务集中管控的具体措施和建议。

1.3 课题研究内容

1. 国铁集团财务集中管控的内涵和外延。
2. 国铁集团财务集中管控的可行性和实施路径。
3. 国铁集团财务集中管控的具体措施和建议。

2.1 国铁集团财务集中管控的内涵和外延

国铁集团财务集中管控是指国铁集团对所属各铁路局集团公司财务工作进行统一管理、统一核算、统一考核的一种管理模式。其内涵包括：统一预算管理、统一会计核算、统一资金管理、统一税务管理、统一资产管理等。

2.2 国铁集团财务集中管控的可行性和实施路径

国铁集团财务集中管控的可行性主要体现在：一是国铁集团具有强大的资金实力和资源禀赋；二是国铁集团具有完善的财务管理体系和制度；三是国铁集团具有先进的财务信息技术支撑。实施路径包括：一是明确国铁集团财务集中管控的目标和任务；二是制定国铁集团财务集中管控的具体措施；三是加强国铁集团财务集中管控的组织和协调。

3.1 国铁集团财务集中管控的具体措施

1. 统一预算管理：国铁集团应制定统一的预算管理制度，明确各铁路局集团公司预算编制、审批、执行、考核等环节的要求。

3.2 国铁集团财务集中管控的组织和协调

国铁集团应成立财务集中管控工作领导小组，负责统筹协调集团财务集中管控工作。各铁路局集团公司也应成立相应的领导小组，负责落实集团财务集中管控的各项要求。

北京交通大学国际合作项目兼职教师

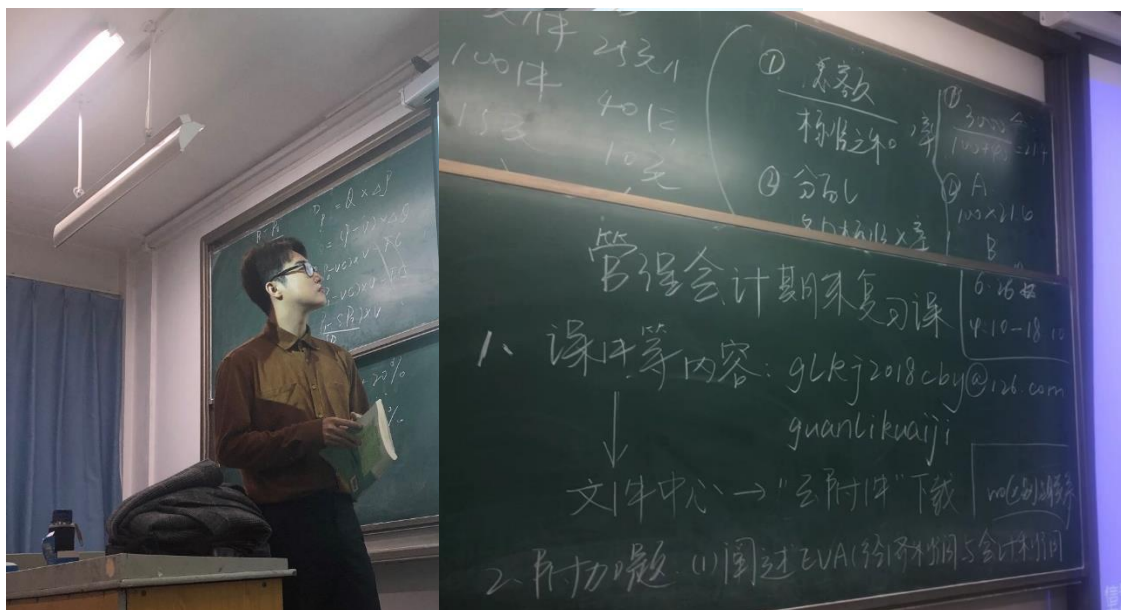
兹证明：

北京交通大学陈炳尧，经济管理学院会计学博士研究生，于 2018 年 9 月至今，任职我单位与北京交通大学合作国际项目兼职教师，为大二大三年级学生讲授《管理会计》（48 学时）、《财务管理》（48 学时）会计学核心专业课程，讲授五个学期累计 240 学时，授课学生人数共计 143 人，取得了良好的教学效果，受到学生的广泛认可与好评。

特此证明。

金桥美中（北京）教育咨询有限公司

2021 年 7 月 9 日



实习证明

学院：经济管理学院

系别：财会

专业：会计

班级：会计 1401 班

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姓名	陈炳尧	性别	男
出生年月日	1996.1.23	籍贯	山东烟台
民族	汉	政治面貌	预备党员
毕业实习时间	2017 年 4 月、2017 年 7 月 3 日—8 月 11 日		
实习单位名称	中国城市和小城镇改革发展中心		
实习单位地址	北京市西城区三里河东路 5 号中商大厦 8 层		
实 习 单 位 鉴 定	由于学习成绩优异、综合素质突出，陈炳尧同学自今年四月被学院推荐于我单位实习。见习期间，能够严格遵守并执行单位的各项规章制度，积极主动的配合其他相邻工作同仁协调完成各种工作任务。认真学习业务知识，在很短的时间内就掌握了工作的要点和技巧，并将其合理的运用到工作中去，主要负责文档整理、账务处理、发票填开、纳税申报等业务，踏实仔细，具备一名会计专业人员的从业素养，能够灵活运用所学的会计专业知识解决工作中遇到的实际困难。同时，陈炳尧同学能够积极主动的向老员工学习，弥补自己的不足。工作主动，学习认真，尊敬他人，待人诚恳，能够做到服从指挥，团结同事，不怕苦，不怕累。见习以来理论水平及操作技能均有很大程度的提高，得到领导和同事们一致好评。  实习单位盖章 2017 年 8 月 11 日		
实 习 成 绩	96		

国际公共交通联合会第100次运输经济委员会会议发言嘉宾

