建成环境对居民出行碳排放的影响研究进展

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摘要 建成环境对居民出行碳排放的影响密切。归纳了居民出行行为理论的发展框架及其理论基础,梳理了建成环境的测度指标及其对居民家庭车辆保有量和出行碳排放的影响关系,并总结两者影响关系的自选择效应。现有研究发现,建成环境测度指标及其对居民出行碳排放的影响结论并不统一,考虑居住自选择的影响,需要进一步丰富相关实证研究。

关键词 建成环境;车辆保有量;居住自选择;出行行为;出行碳排放

气候变化已对全球人类发展造成了很大的威胁[1]。人类活动产生的能源消耗和相关CO_2排放导致全球气候变化已引起了国际社会的广泛关注[2-3]。交通运输是全球能源消耗和CO_2排放增长最快的部门[4-5],减少交通运输CO_2排放被认为是实现减缓气候变化目标的主要途径[6-7],也被认为是减少排放最困难的部门[8-9]。已有文献研究通过城市交通规划来改变个人出行行为[10-12],并进一步探讨对减少出行碳排放的影响[13-14]。较高的人口密度、土地混合使用和步行友好的街道设计与家庭车辆保有量、出行距离和驾车出行频率呈现负相关关系[15-18]。尽管如此,关于建成环境对出行碳排放的影响,理论争论从来没有停止,尤其是考虑到个体心理决定因素(如态度、偏好、动机和目的等)后[19-23]。例如:喜欢步行的居民可能有意识地选择生活在适宜步行的社区。因此,他们步行更多,排放的CO_2更少[24]。此时,建成环境、个体心理决定因素、出行行为与出行CO_2排放的关系就更为复杂。本文主要对建成环境对居民出行碳排放影响的理论和研究进展进行梳理和总结。

1 理论基础

在缺乏理论框架的情况下,公共卫生领域的研究使用了社会生态模型来探索建成环境与流动性(mobility)的关系[25]。社会生态模型最早是由

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Bronfenbrenner在20世纪70年代提出的一种理解人类发展的概念模型,20世纪80年代正式形成理论[26-27]。该模型提出了3种可能影响行为的关键因素:个人水平、社会环境和物理环境[28-30]。由于流动性是人类行为的重要组成部分[31-35],因此它也可能受到不同心理因素的影响。多项与流动性有关的实证研究已经证明了这些关系的有效性和重要性[36-40]。理性行为理论和计划行为理论指出了可以影响行为的有限数量的心理变量[41]。即意图(intention)、对行为的态度(attitude)、主观规范(subjective norms)、感知到的行为控制(behavior control perception)、信仰凸显(belief salience)、过去的行为和习惯(past behavior and habit)、自我效能感(self-efficacy)、道德规范(moral norms)、自我认同(self-identity)等[42]。对出行行为的研究显示,建成环境、社会人口统计属性、自选择(心理因素)和家庭车辆保有量已成为相关实证研究的主要因素[21, 43-48]。汽车保有量是研究建成环境与居民出行行为一个重要的中介因素[47, 49-50],社会人口特征属性通常作为事先控制变量分析建成环境对居民出行行为的影响[47, 51],而探究建成环境、社会人口统计属性与居民出行行为的因果关系时通常会考虑居民偏好、态度和感知等心理因素的作用[43, 45],出行行为最终直接影响出行CO_2排放水平。因此,出行行为理论发展框架总结如图1所示。

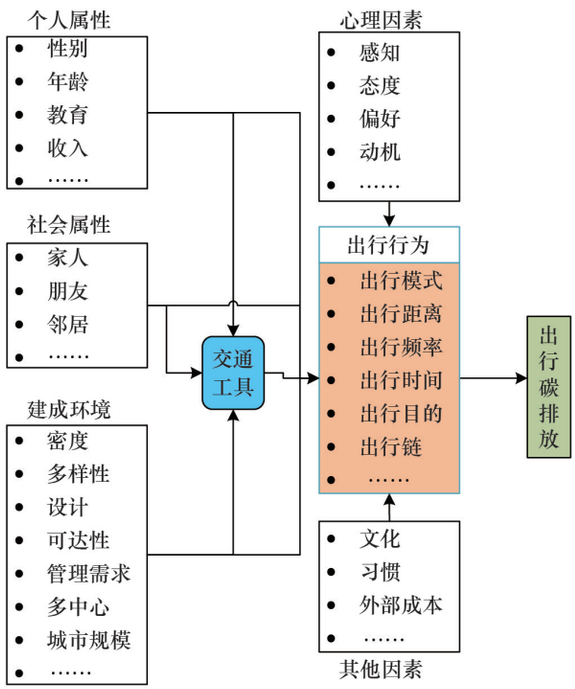

图1　出行行为理论框架

2　建成环境及其对居民出行碳排放的影响

2.1　建成环境及其测度指标

建成环境一词源于城市形态,在20世纪90年代中后期发展中逐渐界定了专有的内涵和外延,即强调以人类活动为核心的空间、时间和社会文化背景所依附的城市实体环境,包括城市用地、建筑环境和它们之间的人类活动;交通基础设施及其服务以及对物理元素的主动性设计和组织[43, 52-53]。

在大量的理论与实证研究中,建成环境逐渐被广泛地接受为5D,包括:密度(density)、多样性(diversity)、设计(design)、目的地可达性(destination accessibility)、距离公共交通的距离/公共交通设施可达性(distance to transit/transit accessibility)[15-16, 54-57]。作者通过对近100篇关于建成环境与出行行为的文献进行梳理,总结出了西方发达国家172个建成环境测度指标,中国城市99个建成环境测度指标。

对比发现,国内外建成环境测度指标比较统一,如5D指标;也有中国特有的建成环境要素,主要体现在社区类型方面,如单位改革房[58]、商品房[48, 58-59]、社会福利房[58]、安置房[60]等。建成环境测度指标文献总结(统计)如表1所示,从有限的文献总结可以看出,5D指标在国内外的实证研究中出现的频率都相对最高、其次是社区类型,这6项建成环境在国内外实证研究文献中的表达比较一致。其他的建成环境及其测度指标国内外的表述不尽相同,这一类建成环境涉及到的文献数量相对偏少,但具体测度指标数量反而较多。

2.2　建成环境对家庭车辆保有量的影响

目前已有不少关于家庭车辆保有量的研究文献。相关实证研究证明,车辆数量的增加导致车辆

表1 建成环境指标文献总结

序号	建成环境维度	频次	频率	测度指标数量	指标数量占比	
1	密度	41	62.12%	29	16.86%	
2	多样性	21	31.82%	16	9.30%	
3	设计	39	59.09%	41	23.84%	
4	目的地可达性	27	40.91%	31	18.02%	
5	公交可达性	14	21.21%	16	9.30%	
6	社区类型	9	13.64%	7	4.07%	欧美国家
7	其他	4	6.06%	32	18.60%	
7.1	公交服务水平	2	3.03%	3	1.74%	
7.2	交通/个人安全	1	1.52%	9	5.23%	
7.3	连接性	1	1.52%	6	3.49%	
7.4	舒适与吸引度	1	1.52%	4	2.33%	
7.5	维护社会资本	1	1.52%	2	1.16%	
7.6	管理需求	1	1.52%	5	2.91%	
7.7	位置	1	1.52%	3	1.74%	
8	文献或指标总数	66	—	172	100.00%	
序号	建成环境维度	频次	频率	测度指标数量	指标数量占比	
1	密度	18	66.67%	6	6.06%	
2	多样性	17	62.96%	18	18.18%	
3	城市设计	8	29.63%	17	17.17%	
4	目的地可达性	11	40.74%	15	15.15%	
5	公交可达性	11	40.74%	10	10.10%	
6	社区类型	9	33.33%	12	12.12%	
7	其他	3	11.11%	21	21.21%	中国
7.1	城市形态	2	7.41%	4	4.04%	
7.2	基础设施特征	1	3.70%	4	4.04%	
7.3	一般性指标	1	3.70%	2	2.02%	
7.4	交通运输水平	1	3.70%	5	5.05%	
7.5	购物设施	1	3.70%	2	2.02%	
7.6	休闲设施	1	3.70%	3	3.03%	
7.7	多中心	2	7.41%	1	1.01%	
8	文献或指标总数	27	—	99	100.00%	

使用量增加[61],随着汽车使用量和汽车行驶里程(VMT)的增加,交通部门的能源消耗和空气污染所占比例显著增加[62]。所以,车辆保有量是建成环境影响出行行为和出行CO_2排放的重要中介因素[47,49-50],合理的建成环境会减少车辆保有量,有效减少出行能源消耗和CO_2排放量。例如随着建成环境人口密度增加,会减少家庭汽车保有量[63-68]、多样性(土地利用混合度)与汽车保有量呈现负相关关系[16];Ewing等[16, 69]和Hong等[16, 69]研究发现,道路网络密度与家庭车辆保有量呈现负相关关系;但是,涉及对家庭汽车保有量的影响比密度和多样性弱[70]。目的地可达性一般包括居住地到中央商务区的距离、工作可达性等[71-72]。实证研究显示,距离中央商务区(CBD)越近,家庭的车辆保有量越低、更倾向于不买车[65, 73];同样的,与工作中心或商务中心越近,能够显著降低开车里程,也能够降低家庭车辆保有量[15, 63];相反,随着与距离CBD距离的增加,对车辆的需求和依赖也增加[74]。家庭与公共交通站的距离会影响到家庭的汽车保有量,例如:Potoglou等[63]发现在居住步行范围内,如果有公

共交通站,会减少家庭汽车保有量;更好的公共交通服务也会减少人们对汽车的持有量[67]。此外,管理需求在近期的研究文献中也作为一个建成环境的维度被学者们讨论,管理需求通常指住宅到停车场的距离、停车场数量或停车服务水平等。一些研究发现,在社区提供低成本的停车场会促使汽车保有量的增加[75-76]。汽车保有量的增加会增加人们对汽车的依赖从而增加出行碳排放,Yang等[77]发现对于非购物出行,汽车保有量是居民日常出行CO_2排放的最关键决定因素。中国农村地区家庭汽车保有量呈现持续增长的趋势[78-79],是农村建成环境影响村民出行碳排放的重要总结因素[80]。所以,Chatman等[81]建议减少社区停车场,以阻碍家庭汽车保有量的增加。

2.3 自选择效应

近期,相关研究开始关注个体心理决定因素,例如个人态度和偏好对出行CO_2排放的影响[29]。居民会因为自我偏好而选择居住环境,从而影响出行行为与出行CO_2排放[43, 45]。Handy等[24]发现喜欢步行的居民可能会有意识地选择生活在适宜步行的社区,因此他们走得更多,排放的CO_2更少。具有可持续消费观念的人更可能选择生活在"新传统(neo-traditional)"或"公共交通出行导向(transit-oriented)"的社区[23, 74, 82-83]。关于自选择对通勤影响的研究,大多数集中在出行模式选择和出行距离两方面。考虑住宅自选择效应后,建成环境通常被认为对通勤模式选择行为有显著影响[83-84]。但Scheiner[85]的研究发现,居民自选择和生活方式都不会对通勤距离产生强烈的影响。一些研究探讨了土地利用特征和居住自选择对通勤多次出行的影响[86-87],并且大多数关于居住自选择理论的实证研究来自西方国家[88]。在中国,Yang等[21]发现中国城市也存在居住自我选择效应,影响居民通勤出行CO_2排放。研究表明,即使在控制居住自选择的显著效应后,建成环境变量的影响仍然具有统计显著性,这使建成环境与出行碳排放之间的关系更复杂[89-91]。

2.4 建成环境对出行碳排放的影响

西方发达国家关于建成环境对出行行为、出行能源消费或CO_2排放影响的研究,学者们已积累了丰富的研究成果[15-16, 23, 55, 92]。中国学者对城市建成环境与居民出行行为的研究处于探索和起步阶段[91],近期的研究文献数量显现了学者们对这一研究领域的浓厚兴趣[93],并主要集中在北京、上海、广州和南京等一线/大城市[93]。

建成环境通过对居民出行行为的影响,进而影响居民出行碳排放[94],这些出行行为以多种方式衡量,包括出行模式选择,出行距离,出行频率,出行目的或出行时间[15, 43, 55, 92]。根据Ewing等[55]的总结,出行频率主要由社会人口统计属性和建成环境决定。建成环境对出行距离更具有决定作用,其次是社会人口统计属性;出行模式选择取决于建成环境和社会人口统计属性,但后者的影响可能更大;对于车辆行驶里程或车辆行驶小时数,建成环境的影响更为显著。该作者在十年后进行的一项类似研究发现建成环境变量对出行行为的综合影响是巨大的[15]。

自20世纪80~90年代开始,相关研究已经提出交通能源消耗和相关排CO_2放量与人口密度负相关[95-96],因为高密度的城市形态促进了公共交通的发展并减少了私家车的使用[97-99];相比之下,工作场所的密度在减少CO_2排放方面比家庭住所密度发挥的作用更大[100]。但Hughes等[101]认为城市规模是出行碳排放最强有力的决定因素,而不是人口密度。Hong[102]发现密度与出行碳排放之间存在非线性关系,人口密度的减排效应在一定程度上不显著。在其他一些研究中,住宅密度与出行碳排放之间的关联并不显著[103-105]。

Zahabi等[106]的研究表明,密度、公共交通可达性和土地利用混合度增加10%,分别意味着与出行有关的温室气体排放减少0.5%、5.8%和2.5%。同样地,Hong等[107]在普吉特海湾地区的研究表明,城市地区住宅密度,土地利用混合度和交叉口密度增加100%,可以减少31.2%~34.4%的交通运输碳排放量。Zhao[108]发现北京城市边缘的城市扩张和蔓延增加了出行距离和汽车使用,导致出行排放量的增加。杨文越等[109]从国家、城市和社区尺度系统综述了建成环境对出行碳排放的影响,并以广州市

为例发现在不同尺度建成环境中,社区尺度的建成环境对居民通勤出行碳排放的影响最显著[110]。

关于建成环境对出行行为、出行能源消费和相关碳排放的量化研究,建成环境测度指标经历了尺度由大到小、视角由宏观到微观、指标内容逐步丰富的过程,杨阳[111]按照研究对象尺度和建成环境量化方法的差别,将相关文献划分为3类:第一类是城市尺度的建成环境;第二类是简单住区尺度的建成环境;第三类是复杂住区尺度的建成环境。表2和表3归纳了国内外研究建成环境影响出行行为与CO_2排放的代表性文献。

表2 国外建成环境与出行行为、出行CO_2排放研究的代表性文献

研究尺度	文献	地域	数据类型	V	主要方法	S	主要考虑的建成环境与主要结论
城市尺度建成环境与出行行为、能源消耗关系	Newman等[112]	全球32城市	AD	×	DA	×	城市人口密度与人均汽油消耗量负相关
	Cervero等[113]	美国	DD	✓	Logit	×	住户300英尺内有商业设施,增加家庭采用公共交通、步行和自行车出行的比例
	Cameron等[114]	全球45各城市	AD	✓	DIA	×	城市出行需求和私人机动车量保有率与城市机动车出行公里数正相关
	Van de Coevering等[115]	欧洲、加拿大、美国	AD	✓	MLR	×	平均出行距离、平均出行时耗均与城市人口规模正相关;平均出行时耗与轨道交通密度负相关
简单住区尺度建成环境与居民出行行为关系	Friedman等[116]	美国	DD	✓	DA	×	郊区住区比传统住区居民更依赖私家车出行
	Cervero等[117]	美国	AD	✓	MSR	×	公交导向型住区中家庭选择步行出行的比例和频率较高,更倾向于公共交通出行
	Handy等[24]	美国	DD	×	DA	✓	结果研究显示传统住区的家庭在购买日常用品时,更多的选择步行出行
	Handy等[43]	美国	DD	✓	OLM FA	✓	郊区比传统社区驾驶距出行距离远
复杂住区尺度建成环境与居民出行行为	Cao等[23]	美国	DD	✓	SUR FA	✓	社区特点影响出行频率,传统设社区更多步行/骑自行车,400米范围内商业类型数量与机动车出行频率负相关
	Zegras等[66]	智利	DD	✓	MNL OLS	✓	到CBD的距离与家庭机动车出行距离负相关,三路路口密度与机动车使用正相关
	Badland等[118]	新西兰	DD	✓	LRA	✓	居住在较不适宜步行街区的就业成年人的居住距离比居住在较适宜步行街区的居民有更长的通勤距离
	Diao等[119]	美国	DD	✓	SRM OLS FA	✓	建成环境因素中的一个标准差异与每户每年5000英里VMT差异有关
	Larranaga等[120]	巴西	DD	×	MIMIC OLM	✓	街道连通性与步行正相关,建成环境影响出行态度
	Ding等[47]	美国	DD	✓	SEM DCM	×	密度、土地利用混合度与出行距离负相关,可达性与出行距离正相关

注:V-车辆保有量;S-自选择;✓(×)-代表文献考虑了(未考虑)此类因素;SRM-空间回归模型;MLR-多元线性回归模型;SUR-看似不相关回归模型;LRA-逻辑回归分析;MIMIC-多重指标多重原因模型;OLM-有序logit模型;DIA-量纲分析;DA-描述性分析;MSR-模态分解回归模型;AD-集计数据;DD-非集计数据。

表3　国内建成环境与出行行为、出行CO_2排放研究的代表性文献

研究尺度	文献	地域	数据类型	V	主要方法	S	主要考虑的建成环境与主要结论
城市尺度建成环境与出行行为或能耗	闫小培等[121]	中国22个城市	AD	×	URM	×	城市规模越与城市居民出行距离、时耗正相关
	万霞等[122]	中国17个城市	AD	×	DA	×	非组团式城市比组团式城市家庭汽车出行时耗更大,并随城市规模增大,家庭汽车出行时耗将显著增大
	孙斌栋等[123]	中国28个城市	AD	×	MLR	×	高密度的城市开发降低平均出行距离和平均出行时耗
住区尺度建成环境与出行行为或能耗关系	马静等[124]	北京	DD	✓	OLSWLS	×	郊区居民比内城居民购物平均出行距离大
	陈燕萍等[125]	深圳	DD	✓	MNL	×	相对于组团中心和非中心区,城市中心和城市副中心的出行者更倾向于选择公共交通出行
	柴彦威等[126]	北京	DD	×	MSLB	×	土地混合利用程度高、居住和就业接近、公共服务设施供给齐备降低家庭出行碳排量。
	姜洋等[105]	济南	DD	×	MSLB	×	超大街区式的高密度开发不利于降低家庭出行能耗
	柴彦威等[127]	北京	DD	✓	SEM	×	距离市中心的距离、公共交通可达性与家庭出行距离正相关;街道人口密度、商业设施供给与地铁站点可达性与家庭出行距离负相关
	Zhao等[128]	北京	DD	✓	MNL	×	可达性、自行车道数量、环境混合型、街道连通性与自行车使用正相关;公共交通服务水平与自行车使用负相关
	Zhao[129]	深圳	DD	✓	PLS-SEM	✓	住区良好的建成环境与汽车使用正相关。
	Feng等[130]	南京	DD	✓	BLR	×	街区设计比社区形式更能影响主动出行(active travel)
	Li等[48]	北京	DD	✓	MLM	✓	地铁站附近社区的多样性和可达性与汽车保有率和出行距离负相关
	Cao等[21]	广州	DD	✓	SEM	✓	土地利用混合型、地铁站密度、路网密度与CO_2排放负相关;公交站密度、到市中心距离、停车场可用性与CO_2排放正相关

注:V-车辆保有量;S-自选择;✓(×)-代表文献考虑了(未考虑)此类变量;MSLB-模式化住区类型比较法; MLM-多项式逻辑模型; BLR-二元逻辑回归模型;CJM- Copula-based联合模型;PLS-SEM -基于偏最小二乘法的结构方程模型;URM-一元回归模型;DA-描述性分析;AD-集计数据;DD-非集计数据。

3　结论

总体来说,建成环境对居民出行行为和出行CO_2排放的影响研究没有得出完全一致的结论。中国交通能源消耗和相关排放的比例普遍低于欧美国家[131-132],发展中国家和发达国家的交通发展差异很大[133-135]。更重要的是,与西方国家相比,中国有特殊的出行态度和偏好[22]。另外,现有研究主要关注城市区域,忽略了对农村地区的研究。与城市相比,农村的建成环境差异巨大,村民自选择的中介影响也不尽相同。比如,在中国农村,农村居民家庭相对固定的宅基地决定了他们基本不能根据自我态度和偏好选择住区位置和环境。基于此,针对中国该领域的研究,本文提出以下研究展望。

1)丰富建成环境测度指标,解析大城市、小城镇和农村地区建成环境测度差异,探索不同类型城市、城镇和农村建成环境对居民出行碳排放的影响机理,为进一步城乡低碳交通政策制定奠定基础。

2）充分考虑车辆保有量的中介作用,探索不同地理环境、不同尺度建成环境对当地居民出行碳排放的影响,考虑多种类型车辆的总结影响,例如共享车、电动车等。因此,考虑中介变量研究中国农村建成环境对农村居民出行CO_2排放的影响可能会得出不同的结论。

3）充分考虑中国居民特有的心理决定因素作用,探索城乡建成环境对当地居民出行碳排放的影响。例如在城乡一体化过程中,当地居民的搬迁经历、心理的差异,对比搬迁前后出行行为的变化等。

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Progress of research on the impacts of built environment on travel carbon emissions

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Abstract The built environment has a close relation with the travel carbon emissions of local residents. This study firstly reviews the development framework and the theoretical basis of the resident' travel behavior theory. Based on this framework, the measurement index of the built environment and its influence on the number of cars owned by the residents and the travel carbon emission are analyzed, and the residential self-selection effect of their relations is revealed. It is shown that the built environment measurement index and its impact on the residents' travel carbon emissions are not uniform.

Keywords built environment; car ownership; residential self-selection; travel behavior; travel carbon emission

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