

Article

An Examination of the Safety Impacts of Bus Priority Routes in Major Israeli Cities

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Abstract: Bus priority routes (BPRs) promote public transport use in urban areas; however, their safety impacts are not sufficiently understood. Along with proven positive mobility effects, such systems may lead to crash increases. This study examines the safety impacts of BPRs, which have been introduced on busy urban roads in three major Israeli cities—Tel Aviv, Jerusalem and Haifa. Crash changes associated with BPR implementation are estimated using after–before or cross-section evaluations, with comparison-groups. The findings show that BPR implementation is generally associated with increasing trends in various crash types and, particularly, in pedestrian crashes at junctions. Yet, the results differ depending on BPR configurations. Center lane BPRs are found to be safer than curbside BPRs. The best safety level is observed when a center lane BPR is adjacent to a single lane for all-purpose traffic. Local public transport planners should be aware of possible negative implications of BPRs for urban traffic safety. Negative safety impacts can be moderated by a wider use of safety-related measures, as demonstrated in BPRs’ operation in Haifa. Further research is needed to delve into the reasons for the negative safety impacts of BPRs under Israeli conditions relative to the positive impacts reported in other countries.

Keywords: safety impacts; bus priority routes; urban roads; crashes; design solutions

1. Introduction

According to worldwide estimates, more than 50% of the global population are currently living in urban areas, and by 2050, this figure will rise to 68%, i.e., more than two-thirds of the global population [1]. Trends in world population growth and distribution may play an essential role in achieving the United Nations’ Sustainable Development Goals, which aim to achieve decent lives on a healthy planet for all by 2030, while balancing the three dimensions of sustainable development: economic, social and environmental [2].

In many countries, rise in urban density is accompanied by a growing use of public transport as a mobility mode [3]. For example, a 2017 report [4], using data from 39 countries, indicated an evolution in urban mobility patterns over the last decade, i.e., growth in the modal share of public transport, together with other sustainable modes like walking and cycling, and, complementing this trend, a marked decrease in car use. Moreover, urban mobility choices were strongly linked to density, with a higher propensity to travel by public transport observed in more densely populated areas. In line with recent developments, current policies for sustainable urban mobility focus on promoting public transport, walking and cycling [5,6].

Ideally, public transportation should provide an efficient and equitable alternative for urban mobility, with associated benefits such as reduced traffic congestion, lower emissions and gains in

individual and public health due to active travel [6–8]. An equitable alternative implies that public transportation should ensure that all population segments and road users receive fair treatment, i.e., that transport facilities and services accommodate all users, including those with special needs, and that benefits are shared and no one is left behind [9–11].

In addition, macro-evaluations suggest that public transport is a safer form of transportation compared with car travel. For example, in the European Union, only 3% of total road fatalities were observed in crashes involving buses and coaches [12]. Estimates in terms of fatalities or serious injuries per billion person-kilometers travelled showed a substantially lower risk for a bus passenger than for a car occupant in the USA [13], several European countries [14], and in Israel [15]. Moreover, studies showed that when public transit travel increases in a particular community, traffic casualty rates tend to decline. For example, Stimpson et al. [16] analyzed traffic data for 100 U.S. cities over 29 years and found that increased use of mass transit was associated with fewer fatalities from road crashes after accounting for climate and the economic costs of driving. Similarly, Litman [13] showed that U.S. cities with more annual transit trips per capita had a lower traffic fatality rate.

As the urban population and traffic grow, local and national governments in various countries frequently address the objective scarcity of space for traffic in urban areas by using bus priority systems to improve mobility and promote public transport use [17–22]. Forms of bus priority systems include bus routes, bus priority lanes and Bus Rapid Transit (BRT). A bus route is a facility designed to physically separate public transport paths from general traffic lanes, so that a higher commercial speed is made possible, e.g., [18]. Bus priority lanes allow a broader range of road layout strategies (e.g., curbside, median-side, etc.) and traffic management solutions (e.g., full-time vs. part-time, exclusive vs. mixed use, etc.). Physical separation from other lanes can be introduced, as well as some forms of signal priority at intersections. A BRT is the ultimate form of bus priority: it is an integrated system combining infrastructure facilities for the exclusive use of buses together with elements of an intelligent management system and services such as centralized operation control, off-board fare collection and level boarding [20,23]. Arguably the most famous example of BRT in Curitiba, Brazil, but various forms of bus priority systems can be currently found in several South American countries, as well as in India, Turkey, Australia, China, USA and European countries [18–27].

Regardless of their form, extensive evidence has shown that bus priority routes (BPRs) reduce passenger travel time and improve the reliability and attractiveness of public transport [21,28,29]. However, less research has been dedicated to the road safety implications of such systems [25,30], while available evidence of their safety impacts is limited and less consistent, sometimes indicating crash increases, particularly in terms of pedestrian crashes.

1.1. Previous Research Findings on the Safety Impacts of BPRs

Several studies have estimated the general safety impacts of BPR systems. For example, Bocarejo et al. [31] found an overall reduction in injury crashes along the bus corridors in Bogota following the implementation of the TransMilenio BRT system, to the extent of 48–60%, compared with a 39% reduction in injury crashes in the whole city (as a comparison-group). However, an increase in crashes was observed around some areas, e.g., in the vicinity of stations, which was apparently related to the higher flows of pedestrians. Duduta et al. [20,28] re-evaluated the data collected by other studies and reported positive impacts of BPR implementation on the safety levels of urban roads in South American countries and India, while in some cases, e.g., Belo Horizonte in Brazil and Delhi in India, an increase in crashes was observed. The summary evaluations of these cases showed that pedestrian injury was one of the major safety problems in BPR operation since pedestrians were involved in only 7% of the total crashes but represented over half of the fatalities from the bus routes [25,28].

Goh et al. [26] modeled bus crashes in Metropolitan Melbourne, Australia, based on the data of a large bus company and found that street segments with bus priority lanes were associated with a lower crash frequency relative to those without dedicated bus lanes. In a complementary study based on police records, Goh et al. [32] found that the implementation of bus priority lanes in the city

was associated with a 14% crash reduction on streets where BPRs were present. In another study, Goh et al. [33] compared traffic conflict patterns in bus priority lanes with mixed traffic conditions and showed that bus lanes reduced conflict occurrences at intersection approaches and bus stop locations. Evidently, bus priority acts to remove bus movements from the general traffic flow and provides new and separate road space for bus traffic, thus reducing crash potential.

Studies of tram priority lanes in Melbourne [34,35] also reported associated crash reductions, yet, an increase in the probability of fatal crashes was found for road sections with tram priorities compared with roads without the priority lanes. The latter was explained by higher speeds in sections with priority lanes, which increased the crash severity in a collision with other road users and, especially, pedestrians. Furthermore, Naznin et al. [36] studied the safety effects of tram priority on 23 arterials in Melbourne, using before–after comparisons, and found a statistically significant adjusted crash reduction rate of 19.4% after the implementation of lane priority measures.

A study conducted in the metropolitan areas of Pittsburgh and Philadelphia examined the impact of non-isolated bus routes on the frequency of all crashes along road segments [37]. It found that the presence of bus routes along roadway segments, i.e., bus lines in mixed traffic, increased the average crash frequency by 27% per year compared with segments with no bus line presence, thus leaving room for the positive safety potential of (separated) BPRs.

Tse et al. [27] estimated the safety impacts of bus priority lanes in Hong Kong, showing decreasing trends in crashes involving public transport vehicles (with mean values of 17–21%) but increasing trends in other vehicle crashes (with mean values of 5–20%). More detailed evaluations in this and other studies [20] showed that most crashes on streets with BPRs occurred outside the dedicated bus lanes. Hence, BPRs' safety is a matter of their impact on general vehicle traffic and pedestrian safety, whereas infrastructure design solutions may be of high importance.

In particular, BPR configurations may have an impact on crash occurrences. The main forms of BPR configurations, as opposed to conventional mixed traffic, are center-lane/median busways, curbside bus lanes and counter-flow bus lanes. Using data on crashes involving pedestrians and vehicles of BPR systems in several South American cities, Duduta et al. [25] found that center-lane configurations were safer compared with curbside systems, while counter-flow bus lanes were the least safe. In addition, the detailed models indicated [25] that a higher number of lanes for general traffic and a higher number of legs at the intersections on bus routes were associated with higher crash figures. Duduta et al. [20] investigated the effects of the introduction of median BPRs in three cities in Mexico, Columbia and India, highlighting a reduction in total crashes, as well as those with fatalities and injuries, compared with figures from the cities as a whole. However, the positive effects in these cases might well be related to an overall improvement in the urban road infrastructure that accompanied the systems' construction, since basic urban infrastructure in developing countries is quite unsafe [38].

In Israel, signalized intersections with median BPRs were characterized by higher figures of total and severe crashes and crashes involving pedestrians, relative to comparison sites where BPR was not present, when controlling for other road characteristics [39].

In a study carried out in Hong Kong [27], the safety impacts of curbside BPRs were estimated, but most results were not statistically significant. Chen et al. [40] examined the safety impacts of curbside BPRs introduced in New York city and found significant increases in vehicle, pedestrian and all crashes, having controlled for changes in comparison-group sites.

A number of studies examined the safety impacts of signal priority measures for bus or tram traffic at intersections but reported mixed results. Shahla et al. [41] modeled the relationships between transit facilities' characteristics and road traffic crashes in Toronto, Canada, and found that the existence of transit signal priority was associated with a crash increase at signalized intersections, both in crashes involving buses/trams and in all crashes (an addition of 25–51%). In contrast, studies conducted in Melbourne reported crash reductions in before–after comparisons following the introduction of signal priority measures for bus or tram traffic [26,32,36]; for example, the expected crash frequency

lowered by 11.1% when bus signal priority was implemented at intersections [32], and there was a reduction rate of 13.9% with tram signal priority [36]. Song and Noyce [42] carried out before–after analyses of data from eleven bus transit corridors in King County, Washington, and found reductions in corridor-level crashes with the implementation of bus signal priority, e.g., a 13% reduction in total crashes and a 5% reduction in fatal and injury crashes.

It should be noted in this context that BPR implementation is typically associated with tangible changes in urban infrastructure and traffic, thereby imposing additional demands on road user behavior and especially on pedestrians. Summaries of international experiences provide recommendations for how to integrate safety into the design and operation of bus routes [18,19,23,28]. They usually emphasize the need for physical separation of the bus lanes, highlighting them by using a different aggregate color, fencing BRT street segments when applicable, and providing signalized intersections only, in order to reduce interactions between buses and other vehicles and prevent uncontrolled pedestrian crossings along the bus routes [39].

In Israel over the past two decades, noticeable efforts have been undertaken to adopt the international recommendations for infrastructure design, as applied to the new BPRs. Despite efforts to reduce safety risks, BPR introduction has sometimes resulted in an increase in pedestrian crash figures [39]. Higher crash frequencies can be attributed to the higher complexity of traffic settings on streets with BPRs, as opposed to regular urban roads and particularly at junctions, as BPRs create more complex crossing configurations and longer waiting times for crossing pedestrians.

1.2. The Current Study Motivation

Previous studies indicate that BPR operation has mixed effects on road safety and that further empirical research is needed to enrich knowledge on the relationship between BPR design and crash occurrences. Pedestrian safety is especially important in this context, since BPRs are intended to increase public transport use and, hence, to attract more pedestrians. In addition, in Israel, the development of BPRs is one of the main policies encouraged today by the Ministry of Transport. Currently, certain BPRs are available in the major cities of Tel Aviv, Jerusalem and Haifa. In the coming years, a rapid development of public transport is expected in many more cities, with ongoing planning for hundreds of BPR kilometers. Therefore, examining design and safety aspects of such systems is crucial in order to understand and address the risks that BPR systems may present.

Being aware of the discrepancy in international research findings and the importance of local context, this study was initiated to examine the safety impacts of the BPRs that have been implemented in Israel over the last decades. Such formal evaluations were not performed in the past, except for one study that examined crash changes on BRT routes in Haifa during the first two years of operation [43]. The current study applied longer time periods than [43] and also considered BPR safety impacts in additional cities. This study contributes to the literature by showing that, in general, negative safety impacts of BPRs can be expected on busy urban roads, yet the extent of the impact differs depending on BPR configurations. The current study compares three BPR configurations: curbside bus lanes, center-lane bus routes near two lanes for general traffic, and center-lane bus routes near a single traffic lane, indicating that the center-lane bus routes have less harmful safety impacts relative to the curbside. Moreover, center-lane bus routes adjacent to a single traffic lane appear to be most promising in moderating crash increases following BPR introduction on urban roads.

The remainder of the paper is structured as follows. Section 2 describes the study framework, data and methods. Section 3 shows the evaluation results. Section 4 provides a general discussion of the study's findings in the context of international research and their implications for planning bus priority routes. Section 5 presents the main conclusions for local urban planners.

2. Materials and Methods

2.1. The Study Framework

This study aimed to examine the safety impacts of BPRs, which were recently implemented in Israel. The safety impacts of this measure (i.e., crash changes associated with BPR operation) should preferably be assessed by means of after–before analyses of crash figures observed on the road sites with treatment, while accounting for the crash changes that occurred at comparison-group sites [44]. However, in case of the unavailability of crash data for the before period, a cross-section analysis can be applied [45], where crash rates are compared between the treated sites (with BPRs) and comparison-group sites, in similar (after) time periods. In most cases estimated in this study, after–before analyses were applied, but in one case (in Jerusalem), a cross-section analysis was conducted. In addition, to examine the findings’ stability, several comparison-groups or several after time periods were considered in each study case.

The study focus was on median and curbside BPRs operated on busy urban roads with high traffic volumes and pedestrian activity, since such configurations are common in local practice.

2.2. The Study Cases and Data

For the study, urban roads with BPRs were selected in three cities: Tel Aviv, Jerusalem and Haifa. These are the three biggest cities of the country, situated in the center, north and the east. All cities are densely populated, housing many business, employment and education centers (which creates high levels of daily commuter incoming traffic) and have highly developed systems of bus public transport. The BPRs selected for this study were established in the past two decades and are still in operation. In total, five cases were evaluated in the study: a curbside BPR in Tel Aviv, a center-lane BPR in Jerusalem and groups of roads with three BPR configurations in Haifa—a center-lane BPR near two traffic lanes, a center-lane BPR near one traffic lane and a curbside BPR. Figure 1 shows examples of the BPR settings used in the study cases. The case study maps are shown in Appendix A.



Figure 1. Examples of bus priority route (BPR) settings in the study cases: (a) a curbside BPR in Tel Aviv, (b) a center-lane BPR in Jerusalem, (c) a center-lane BPR near two traffic lanes in Haifa, (d) a center-lane BPR near one traffic lane in Haifa, and (e) a curbside BPR in Haifa.

Each study case was defined in terms of time and space. The time frame included three periods: *before*, with no BPR in place, *during* the bus route construction, and *after*, with the bus route in operation. The space frame comprised the full list of road sections and junctions included in the BPR. The construction period was used for a correct definition of the before and after periods but was not considered in crash analyses as it is not relevant to BPR safety performance. For each BPR, a comparison-group of streets from the same city, with similar traffic functions and infrastructure settings but without BPRs, was fitted, or, alternatively, the whole city served as a comparison-group (in Haifa). In all cases, the crash data were extracted from the national traffic crash files, which are based on the police-collected crash records. In Haifa, the crash data were obtained from the Haifa municipality traffic crash database, which is based on the national files but is a refined source since the records went through an additional verification of crash locations by means of manual re-checks in the police archives.

2.2.1. A BPR in Tel Aviv: Ibn Gvirol Street

This is a 2.8 km urban dual-carriageway with a raised median, two travel lanes for general traffic, and a curbside BPR in each direction (Figure 1a). The BPR operates in the morning and evening hours (6:30–10, 14–19) on working days; in other hours, parking is permitted on the bus lane. The street crosses the city of Tel Aviv from north to south, has plenty of pedestrian attractions and cycling lanes on the sidewalks, and is characterized by high pedestrian, cyclist and vehicle activity. The street was reconstructed, and the BPRs were established between January 2007 and February 2011. For the study, the before period was defined as 2003–2006 and the after period from March 2011 until the end of 2014. As a comparison-group, five collector roads from Tel Aviv were selected, each with a similar layout, high traffic volumes and no BPRs (the total length was 7.8 km); see Appendix A for the road locations on the city map. Accounting for the hours of BPR operation, several crash analyses were conducted, considering morning, evening or all hours of BPR operation, relative to similar or other hours of the comparison-group streets or to other day hours of the study street. The crash data were examined for working days.

2.2.2. A BPR in Jerusalem: Hebron Road

This is a 2.7 km road with a central bidirectional busway, which has operated since 2005. A fencing separation from the general traffic on street sections is present (Figure 1b). This BPR operates the whole day (except for Saturdays, when public transport is closed in the country). Since exact information regarding the period of construction was unavailable, a cross-section crash analysis was applied in this case, with two after periods: (1) the initial six years of the busway operation, 2005–2010, and (2) the subsequent five years, 2011–2015. As comparison-group sites, nine collector roads from Jerusalem were selected, each with a dual-carriageway layout: several travel lanes per direction, raised median, high traffic volumes and no BPRs (total length 7.9 km); see Appendix A for road locations. The crash data for all hours were examined.

2.2.3. BPRs in Haifa

A BRT system called “Matronit” was established in the Haifa metropolitan area between 2006 and 2013 and launched in August 2013. It comprises over 40 km of bus priority routes for the operation of articulated buses. For monitoring purposes, BPR configurations of the system were subdivided into homogeneous groups, accounting for the road layout, traffic and urban surrounding characteristics [43]. In this study, three BPR configurations were examined (Figure 1c–e): a center-lane busway near two lanes for general traffic, a center-lane busway near one lane for general traffic, and a curbside bus lane. All settings belong to divided arterial or collector roads.

The first configuration has a one-way bus lane on each side of the raised median; the bus lane is segregated both physically, by a low curb, and visually, by means of red-colored aggregate. Near road junctions, where bus stops are present, the bus routes’ physical segregation from other traffic is even

stronger, by means of barriers. A curbside lane configuration has bus traffic on the right-side lane, adjacent to two left lanes for general traffic; the bus-lane is indicated by yellow markings and a red aggregate color [43]. The study groups included nine, three and two streets with BPRs from the city of Haifa, with a total length of 6.6, 1.2 and 6.9 km, respectively (see Appendix A for road locations on the city map).

As a comparison-group, the numbers of traffic crashes in the city as a whole were used, similar to previous studies on the topic [20]. For each study site in Haifa, detailed information on the period of construction was collected, and a three-year before period was defined prior to the roadworks. For all sites, three after periods were considered, starting from August 2013 and comprising 2, 3 and 3.5 years of the BPRs' operation, respectively. Several after periods were considered in the Haifa cases, in accordance with crash data availability during the study, and also enabling us to consider an adaptation effect. The latter was suspected from local experience as, following some BPRs' introduction in previous decades, a substantial increase in crash numbers was observed in the initial period of BPR operation.

2.3. Crash Analyses

In most study-cases, after–before crash analyses were applied. For after–before analyses of crash changes, odds-ratio (OR) estimates with a comparison-group and weighted mean effect were used, as this is widespread in road safety evaluations [44,46]. To measure the safety impact of treatment (BPR operation), the number of crashes observed in the after period on the study sites was compared with the number of crashes that would have occurred in the absence of treatment [46]. The latter was estimated based on the crash changes observed, in the after versus before period, at the comparison-group sites. The odds-ratio is estimated as:

$$\theta_i = [X_a^i/X_b^i]/[C_a^i/C_b^i] \quad (1)$$

where: θ_i —the estimate of the safety effect observed at the study site i ; X_a^i and X_b^i —the numbers of crashes at the study site i in the after and before periods; C_a^i and C_b^i —the numbers of crashes in comparison-group (for site i) in the after and before periods. The before and after periods of the comparison-group were matched to the periods of the study site.

For a group of sites, a weighted mean effect (WME) and its confidence interval are estimated, as described in [44,46]. The confidence interval of the safety effect for a single site is estimated similarly. The safety effect is reported as (WME-1)*100; both the mean safety effect and its confidence interval are presented in percentages. Negative values reflect a crash reduction, whereas positive values reflect a crash increase. The crash reduction is significant when the whole confidence interval is negative. When the confidence interval includes zero (has negative and positive values), the result is not significant, but a decreasing or increasing crash trend can be indicated depending on the mean effect's value. When the mean effect of crash changes is within several percent only (below 5%), its practical meaning is limited, and such a result is interpreted as “no change”.

In one study case (in Jerusalem), due to the unavailability of crash data for the “before” period, cross-section analysis was applied. In the cross-section analysis, crash indices were compared between the treatment and the comparison-group sites in the after periods, using a method described in [45]. The significance of differences in crash values of the two groups of sites was estimated using a T-statistics, as follows:

$$T = \frac{\ln(\theta)}{\sqrt{\frac{1}{N_1} + \frac{1}{N_2}}} \quad (2)$$

where: $\theta = R_1/R_2$; N_1 —the total number of crashes in the treatment group; N_2 —the total number of crashes in the comparison-group; R_1, R_2 —the crash indices of the groups. The T-statistics is tested using the null hypothesis that there is no difference between the groups. If a probability for the T-value is low ($p < 0.05$), the null hypothesis is rejected, and a significant difference between the compared groups

of sites is observed. A T-test is suitable in this case because the *log OR* distribution is asymptotically normal [47]. This asymptotic approximation does not give a meaningful result if any of the counts is very small, but for the current study (in Jerusalem's case), this approximation is suitable. We compared normalized crash indices of the treatment and comparison-group sites, i.e., the average number of crashes per 1 km of road (for road sections) and the average number of crashes per intersection (having counted the total number of intersections on the street).

The crash numbers were analyzed separately for road sections and intersections and comprised total injury crashes as well as the subgroups of severe crashes (fatal plus serious), crashes with pedestrian injury, and crashes involving buses; the subgroups were subject to data sufficiency.

3. Results

Table 1 shows the crash numbers observed on the study sites and in comparison-group sites. Tables 2–4 provide the results of crash analyses.

3.1. The BPR in Tel Aviv

During the curbside BPR operation on Ibn Gvirol street, severe crashes and crashes involving buses were not frequent (see Table 1a), while the shares of crashes involving pedestrians were substantial, in the range of 30–60%. High shares of pedestrian crashes were also observed at other hours (see *Comparison 2*), indicating that pedestrian crashes are pertinent to this street due to the high pedestrian presence and not necessarily related to the bus lane operation. The after–before comparisons showed (Table 2) that BPR operation hours were associated with increasing crash trends on road sections and at junctions, and, particularly, in pedestrian crashes at intersections. In injury crashes at junctions, stronger increasing trends were observed in the morning rather than in the evening hours of BPR operation. In injury crashes on sections, the range of changes was wide, with both increasing and decreasing trends depending on the comparison-group. For pedestrian crashes at intersections, most results indicated an increasing trend. In total, the period of BPR operation on this street was associated with deteriorating trends in road safety.

3.2. The BPR in Jerusalem

During the BPR operation periods on Hebron Road, the shares of severe, pedestrian and bus crashes (out of the total) were tangible (Table 1b). The shares of pedestrian and bus crashes at junctions were higher than in the comparison-group, apparently due to higher pedestrian activity and bus traffic on the road. The comparisons showed (Table 3) that average crash numbers at the study sites were consistently higher than at the comparison sites, thus suggesting that the safety level of an urban road with a center-lane BPR could be lower than that of similar roads without bus routes. This result supports a previous local study, which found higher crash numbers at intersections with median bus routes compared with regular junctions [39].

3.3. The BPRs in Haifa

The after–before comparisons showed (Table 4) that on streets with a center-lane BPR near two traffic lanes, decreasing crash trends were observed along the sections but increasing trends at intersections. This was in line with an expectation that a center-lane BPR lessens the interaction of buses with other vehicle traffic on road sections, thus reducing the risk of crashes, while the higher complexity of traffic settings at junctions with bus routes may increase the crash risk. The changes in severe crashes varied a lot over the different periods due to low crash figures. The decreasing trends in section crashes strengthened over-time, reaching a significant decrease in total crashes in the period of 3.5 years of BPR operation, whereas the increasing trends in junction crashes weakened over-time. Hence, an over-time improvement in the safety level of center-lane BPRs can be stated, as was also found in other countries [20].

Table 1. Total numbers of crashes observed at the study and comparison-group sites. (Percentages of specific crash types out of total injury crashes are given in parentheses).

a—Ibn Gvirol Street, Tel Aviv									
Sites *, Hours	Period	On Road Sections				At Intersections			
		Injury Crashes	Severe Crashes	Pedestrian Crashes	Bus Crashes	Injury Crashes	Severe Crashes	Pedestrian Crashes	Bus Crashes
With BPR, 6:30–10	before	11	2 (18%)	5 (45%)	1 (9%)	19	1 (5%)	3 (16%)	2 (2%)
	after	7	1 (14%)	4 (57%)	1 (14%)	16	3 (19%)	5 (31%)	3 (19%)
With BPR, 14–19	before	23	1 (4%)	5 (22%)	1 (4%)	40	1 (3%)	9 (23%)	5 (13%)
	after	17	5 (29%)	5 (29%)	2 (12%)	18	3 (17%)	9 (50%)	0
Comparison 1, 6:30–10	before	19	0	4 (21%)	1 (5%)	63	6 (10%)	8 (13%)	5 (8%)
	after	9	1 (11%)	2 (22%)	2 (22%)	29	3 (10%)	6 (21%)	1 (3%)
Comparison 1, 14–19	before	39	1 (3%)	6 (15%)	0	120	8 (7%)	9 (8%)	4 (3%)
	after	24	5 (21%)	7 (29%)	1 (4%)	56	4 (7%)	9 (16%)	3 (5%)
Comparison 1, other hours	before	97	3 (3%)	16 (16%)	2 (2%)	291	18 (6%)	48 (16%)	15 (5%)
	after	57	8 (14%)	27 (47%)	3 (5%)	149	13 (9%)	27 (18%)	10 (7%)
Comparison 2, btw 10–14	before	21	2 (10%)	6 (29%)	0	39	4 (10%)	19 (49%)	4 (10%)
	after	18	2 (11%)	9 (50%)	2 (11%)	17	3 (18%)	8 (47%)	1 (6%)
b—Hebron Road, Jerusalem									
Sites	Period	On Road Sections				At Intersections			
		Injury Crashes	Severe Crashes	Pedestrian Crashes	Bus Crashes	Injury Crashes	Severe Crashes	Pedestrian Crashes	Bus Crashes
With BPR	after 1	50	13 (26%)	13 (26%)	10 (20%)	198	25 (13%)	39 (20%)	27 (14%)
	after 2	59	12 (20%)	14 (24%)	12 (20%)	123	11 (9%)	33 (27%)	22 (18%)
Comparison-group	after 1	65	10 (16%)	16 (25%)	7 (11%)	270	20 (7%)	44 (16%)	22 (8%)
	after 2	60	15 (25%)	19 (32%)	12 (20%)	219	23 (11%)	48 (22%)	36 (16%)
c—Streets with BPRs, Haifa									
BPR Configuration	Period	On Road Sections				At Intersections			
		Injury Crashes	Severe Crashes	Pedestrian Crashes	Bus Crashes	Injury Crashes	Severe Crashes	Pedestrian Crashes	Bus Crashes
Center-lane BPR near two lanes	before	167	32 (19%)	41 (25%)	4 (2%)	254	26 (10%)	35 (14%)	3 (1%)
	after #	36	7 (19%)	9 (25%)	3 (8%)	160	11 (7%)	26 (16%)	13 (8%)
Center-lane BPR near one lane	before	22	6 (27%)	11 (50%)	0	27	2 (7%)	11 (41%)	1 (4%)
	after #	3	1 (33%)	0	1 (33%)	7	0	3 (43%)	0
Curbside BPR	before	13	5 (38%)	2 (15%)	1 (8%)	60	10 (17%)	10 (17%)	0
	after #	24	3 (13%)	6 (25%)	0	65	7 (11%)	15 (23%)	2 (3%)

* Comparison 1—other streets; Comparison 2—the study street, in day hours without bus-lane operation. # 3.5 years.

Table 2. Crash changes during BPR operation period on Ibn Gvirol street, Tel Aviv.

Comparison: Sites, Hours	Crash Type	Mean Effect	95% Confidence Interval		Meaning
With BPR, morning * vs. Comparison-group 1, morning *	Total injury, on sections	+34%	−61%	+362%	IT
	Total injury, at junctions	+83%	−18%	+306%	IT
	Pedestrian, at junctions	+122%	−63%	+1218%	IT
With BPR, evening * vs. Comparison-group 1, evening *	Total injury, on sections	+20%	−46%	+169%	IT
	Total injury, at junctions	−4%	−49%	+83%	No change
	Pedestrian, at junctions	0%	−73%	+269%	No change
With BPR, all * vs. Comparison-group 1, all *	Total injury, on sections	+24%	−37%	+144%	IT
	Total injury, at junctions	+24%	−24%	+103%	IT
	Pedestrian, at junctions	+32%	−53%	+273%	IT
With BPR, all * vs. Comparison-group 1, other hours	Total injury, on sections	+20%	−35%	+123%	IT
	Total injury, at junctions	+13%	−29%	+79%	IT
	Pedestrian, at junctions	+107%	−16%	+412%	IT
With BPR, morning * vs. Comparison-group 2	Total injury, on sections	−26%	−76%	+132%	DT
	Total injury, at junctions	+93%	−20%	+364%	IT
	Pedestrian, at junctions	+296%	−24%	+1966%	IT
With BPR, evening * vs. Comparison-group 2	Total injury, on sections	−14%	−65%	+110%	DT
	Total injury, at junctions	+3%	−53%	+129%	No change
	Pedestrian, at junctions	+138%	−31%	+720%	IT

* In BPR operation hours. IT—increasing trend, DT—decreasing trend.

Table 3. Comparing crash indices on Hebron Road, Jerusalem, and at comparison-group sites by period and crash type.

Sites	After Period 1 (6 Years)						After Period 2 (5 Years)					
	On Road Sections			At Intersections			On Road Sections			At Intersections		
	Injury Crashes	Pedestrian Crashes	Bus Crashes	Injury Crashes	Pedestrian Crashes	Bus Crashes	Injury Crashes	Pedestrian Crashes	Bus Crashes	Injury Crashes	Pedestrian Crashes	Bus Crashes
With BPR *	18.8	4.9	3.8	15.2	3.0	2.1	22.2	5.3	4.5	9.5	2.5	1.7
Comparison-group **	8.3	2.0	0.9	6.8	1.1	0.6	7.6	2.4	1.5	5.5	1.2	0.9
Differences (p-value)	<0.01	0.03	0.01	<0.01	<0.01	<0.01	<0.01	0.03	0.01	<0.01	<0.01	0.02

* 2.66 km, 13 intersections. ** 7.87 km, 40 intersections.

Table 4. Crash changes during BPRs' operation in Haifa, in various after periods.

	2 Years *	3 Years *	3.5 Years *			
Crash Type	Mean Effect	Mean Effect	Mean Effect	95% Confidence Interval [#]	Meaning [#]	
Center-lane BPR near two lanes						
Severe crashes, on sections	+14%	−33%	−29%	−74%	+98%	DT
Total injury crashes, on sections	−24%	−38%	−38%	−60%	−4%	Decrease
Pedestrian crashes, on sections	−39%	−48%	−54%	−82%	+17%	DT
Severe crashes, at junctions	+14%	−19%	+3%	−63%	+188%	No change
Total injury crashes, at junctions	+34%	+18%	+15%	−9%	+44%	IT
Pedestrian crashes, at junctions	+136%	+81%	+33%	−42%	+205%	IT
Bus crashes, at junctions	+135%	+72%	+73%	−60%	+641%	IT
Center-lane BPR near one lane						
Total injury crashes, on sections	−70%	−78%	−81%	−97%	+27%	DT
Pedestrian crashes, on sections	−93%	−96%	−96%	−100%	+88%	DT
Total injury crashes, at junctions	−32%	−47%	−48%	−78%	+23%	DT
Pedestrian crashes, at junctions	+52%	0%	−16%	−82%	+284%	DT
Curbside BPR						
Total injury crashes, on sections	+64%	+68%	+61%	−19%	+218%	IT
Severe crashes, at junctions	−21%	−36%	−32%	−76%	+94%	DT
Total injury crashes, at junctions	+30%	+20%	+17%	−19%	+69%	IT
Pedestrian crashes, at junctions	+28%	+56%	+51%	−35%	+251%	IT

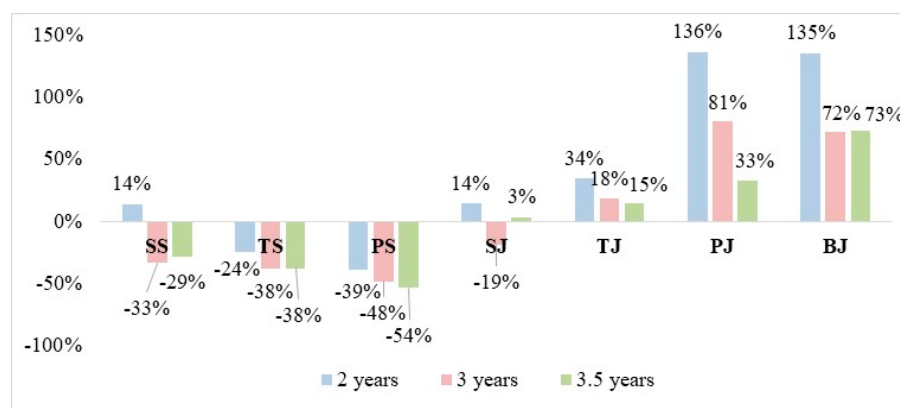
* After periods. # For mean effect in 3.5 years' after period. IT—increasing trend, DT—decreasing trend.

As far as streets with a center-lane BPR near one traffic lane are concerned, descending trends appeared both in section and junction crashes, and the reduction intensified over-time. As for pedestrian crashes at intersections, an increasing trend appeared over the first 2 years of operation, but a decreasing trend in the longer term was observed. Overall, this BPR type is associated with a positive change in the safety level.

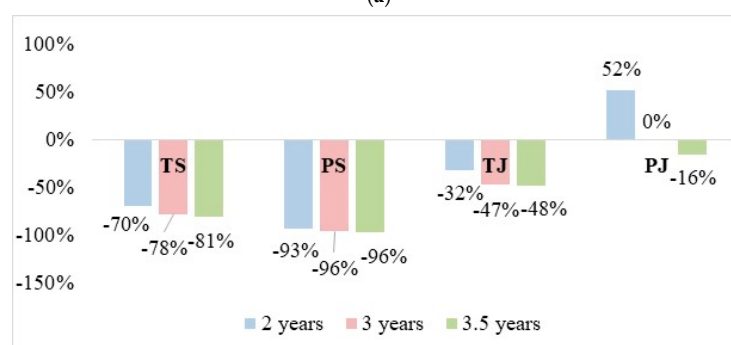
On both types of center-lane BPRs in Haifa, pedestrian crashes exhibited decreasing trends on sections that, similarly to the previous study [43], can be related to the presence of raised medians with obstacles and fences, thus preventing uncontrolled pedestrian crossings. Conversely, pedestrian crashes at intersections showed increasing trends, particularly in the earliest period of the BPRs' operation. Such a result is expected due to (i) the higher complexity of crosswalk settings at intersections with center-lane BPRs on dual-carriageway roads and (ii) longer waiting times for pedestrians. Similar problems have been raised in previous studies in Israel [39,43].

On streets with a curbside BPR, increasing crash trends appeared following BPR operation, both along the road section and at junctions; on the other hand, severe crashes showed consistent decreasing trends. Whereas the increasing trends in total crashes slightly moderated over-time, they intensified in pedestrian crashes at junctions. In general, the curbside BPR appears to be associated with worse performance relative to center-lane BPRs. In contrast to center-lane BPRs, a curbside configuration does not prevent vehicles from entering the bus lane (e.g., those who wish to stop near a sidewalk or plan to turn); thus, higher bus frequency may lead to an increase in crash occurrences, in line with [43].

Figure 2 provides a visual presentation of the crash changes observed on streets with BPRs in Haifa, in various after time periods. For streets with center-lane BPRs, a consistent improvement of safety effects, i.e., a stronger reduction or lower increase in longer after periods, can be noticed for various crash types. Similar over-time changes are less prominent for streets with curbside BPRs.

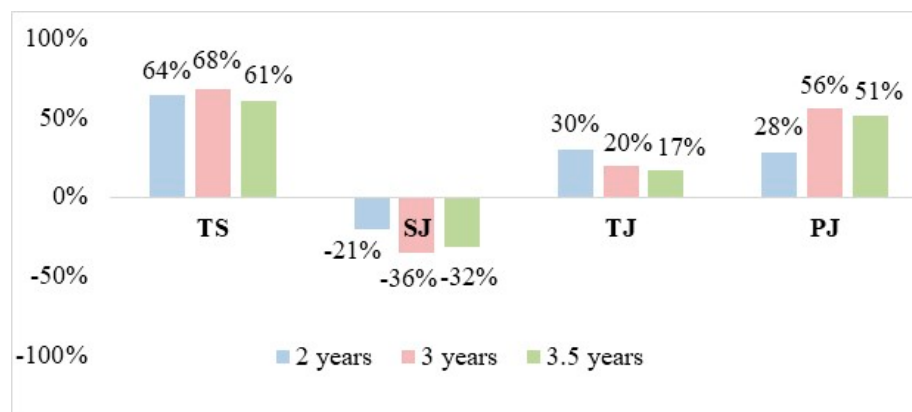


(a)



(b)

Figure 2. Cont.



(c)

Figure 2. Safety effects of BPRs in Haifa in various after periods: (a) the center-lane BPR near two lanes; (b) the center-lane BPR near one lane; and (c) the curbside BPR. Crash types: SS—severe, on sections; TS—total, on sections; PS—pedestrian, on sections; SJ—severe, at junctions; TJ—total, at junctions; PJ—pedestrian, at junctions; BJ—bus crashes, at junctions.

4. Discussion

The study findings demonstrated that BPR affects the safety level of urban roads. Unlike the results of studies from South American countries and Australia, which reported crash reductions associated with BPR systems [20,26,28,32], the experience in Israel indicates that, in general, crash increases should be expected. Although the safety effects in this study were not significant and, thus, a substantial worsening in road safety associated with BPRs cannot be stated, the increasing trends were consistent across the majority of the crash types and the bus routes examined and, hence, cannot be ignored.

The evidence from the Israeli experience indicates that urban locations with bus priority route features tend to have higher crash occurrences compared with similar sites without them. The reasons for this refer to the higher complexity of traffic settings on urban streets with BPRs and the greater pedestrian activity on streets with intensive public transport. Particularly at intersections, BPR settings increase the time of crossing for both vehicles and pedestrians, which may increase the probability of faulty or unsafe behaviors by road users [28,43].

A positive safety effect of BPR systems in developing countries can also be related to overall improvements in urban infrastructure on the roads where BPRs are implemented, relative to previous (frequently unsafe) conditions [38]. Regarding the differences of Israeli findings (in this and previous studies—[39,43]) compared with Australian research, which mostly reported positive safety effects of bus and tram priority lanes [26,32,34–36], the reasons for this are less clear and should be explored in the future. The higher complexity of BPR settings, with more substantial changes in urban road infrastructure, could be one of the reasons leading to negative safety impacts of BPRs in Israel. Another reason could be related to BPR applications on mostly busy urban roads with high travel speeds, which might increase both crash occurrences and their consequences. The impact of bus signal priority at BPR intersections still needs to be estimated for Israeli conditions, while in Australian and US studies, associated crash reductions were found on bus and tram transport corridors [26,32,36,42].

The safety effects of the BPR system in Haifa were more positive, relative to similar routes in other cities. The reason may lie in the stricter adoption of the lessons of international experience regarding the integration of safety by design and operation of Haifa's BPRs. Infrastructure solutions such as bus lane segregation, separate carriageways on sections with heavy traffic, the use of colored aggregate, fencing street segments where possible and, finally, the presence of signalized intersections and pedestrian crossings were systematically applied in Haifa, in line with international guidelines and design recommendations [18,19,23,28].

The safety level of streets with BPRs depends on selected traffic settings. Our study found that curbside BPRs were associated with increasing trends in crashes, particularly at junctions. Negative safety effects of curbside bus lanes were also reported in other countries [27,40]. This finding is also supported by a literature review of bus priority schemes [22], which indicated that higher traffic volumes and right-turn rates in the adjacent general-purpose lane cause increasing interactions between buses and other vehicles (on a curbside BPR), resulting in decreased bus lane capacity and safety level.

The safety impacts of center-lane BPRs coupled with two traffic lanes were negative in Jerusalem's case but more positive in Haifa, where decreasing trends in total and pedestrian crashes on road sections were faced by increasing crash trends at intersections. Moreover, center-lane BPRs, coupled with a single traffic lane, were associated with positive safety performance both on sections and at junctions. The study findings generally support the international experience, which relates lower crash risks to center-lane versus curbside BPRs [20,25].

The consistent decrease in crash figures in the center-lane BPRs adjacent to a single traffic lane points to a positive "traffic calming" effect on streets with BPRs (i.e., reducing general traffic lanes). In urban planning, traffic calming is a common policy for improving safety in residential areas and a rising concept of priority change in city centers [48,49]; it highlights a greater concern on the part of traffic planners for the safety of vulnerable users, such as pedestrians and cyclists [3,48–50]. Combining BPR planning with traffic calming considerations may be a promising approach for creating a safer urban environment that is specially focused on pedestrian safety in the vicinity of public transport routes.

In line with international experience [20,28], the study findings suggest that design solutions such as a physical segregation of BPRs, the use of colored pavement, the fencing of street sections, and the reduction of the number of traffic lanes may decrease safety risks on streets with BPRs. However, despite the use of signalized intersections with controlled pedestrian crosswalks, increasing trends were observed in pedestrian crashes at junctions, in all types of the BPRs examined in this study. Thus, the use of signalized intersections is not sufficient, and advanced engineering solutions are needed to reduce the risk of pedestrian injury at junctions with BPRs.

Given the rising congestion of the transportation network and the increasing role of public transportation in sustainable urban development [5], the popularity of BPRs is expected to grow in the future. When promoting BPRs in cities, the whole range of implications of such systems should be accounted for, including road safety. Previous research showed extensively that bus priority systems reduce passenger travel time and improve the attractiveness of public transport [21,28,29]. In contrast, assessing the safety impacts of BPRs is still limited since analyses were only carried out in a few countries and much more empirical research is required concerning both the general effects of these systems on urban traffic safety and the implications of specific design solutions. Negative safety impacts can be expected in this context, as observed in Israel and some other countries. Local urban planners should be aware of crash increases associated with BPR operations, and thus more attention should be given in the planning process to safety auditing of the selected design solutions.

The limitations of the current study consist in the limited number of sites examined and the low amount of crash data, which are not always sufficient to produce statistically significant results. The crash evaluations were related to BPR configurations, but results are general and hence no impact of specific design solutions can be assessed. Further studies are needed to provide more detailed evaluations of specific solutions applied to BPRs and to support future selections of design alternatives. Assessing safety impacts of more BPR systems, with different design configurations and urban contexts, may help in decreasing uncertainty.

In addition, being aware of differences in the safety impacts of BPRs observed in Israeli practice compared with the Australian experience, further in depth studies of BPR impacts on crashes and road user behaviors would be useful for local conditions. There is also high interest in the results of safety

evaluations of BPRs in other developed countries, particularly in Europe, which are not yet present in the research literature.

5. Conclusions

This study aspired to contribute to the empirical knowledge on the safety impacts of BPRs, using the analysis of crash changes observed following the introduction of BPRs in three big Israeli cities. The study showed consistently that a BPR implementation on busy urban roads can result in increasing trends for various crash types, in particular those involving pedestrians. Local public transport planners should be aware of the possible negative implications of BPRs for urban traffic safety. At the same time, negative safety impacts can be moderated by the selection of BPR configuration and a wider use of safety-related measures, as demonstrated in the cases of the “Matronit” BPRs’ operation in Haifa. Center lane BPRs were found to be safer than curbside BPRs under local conditions. The best safety level for BPR operation can be expected under a combination of median BPR configuration and reduced general traffic, i.e., a center-lane BPR near a single lane for all-purpose traffic. Further research is needed to delve into the different safety impacts of BPRs observed under Israeli conditions, related to other countries.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

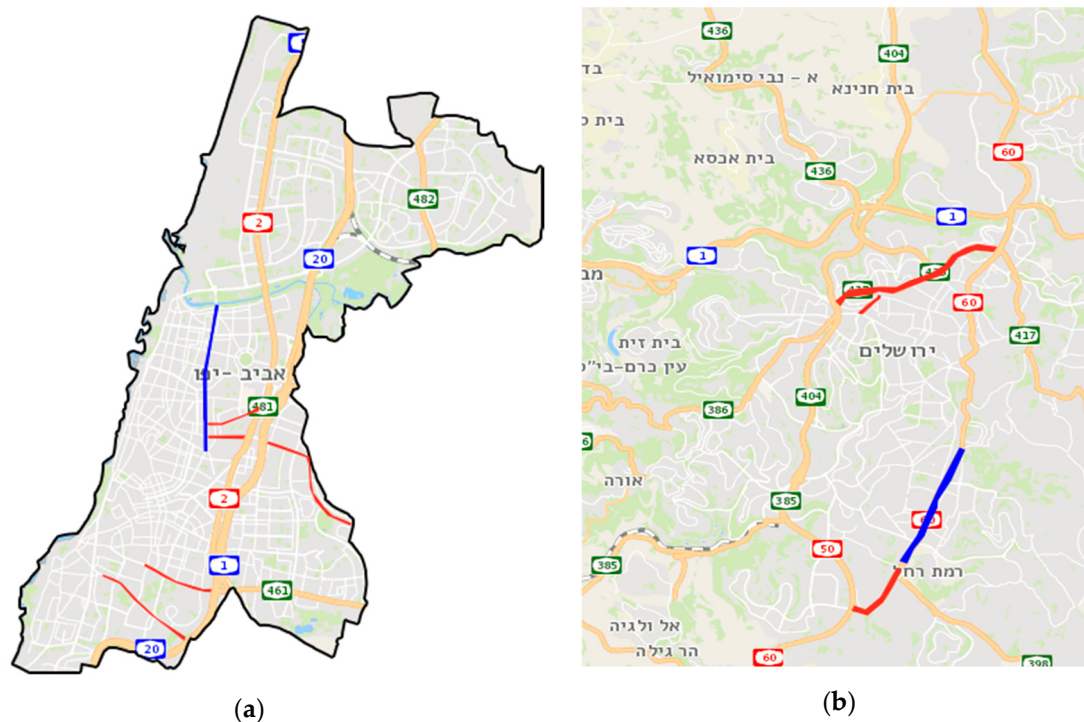


Figure A1. Cont.

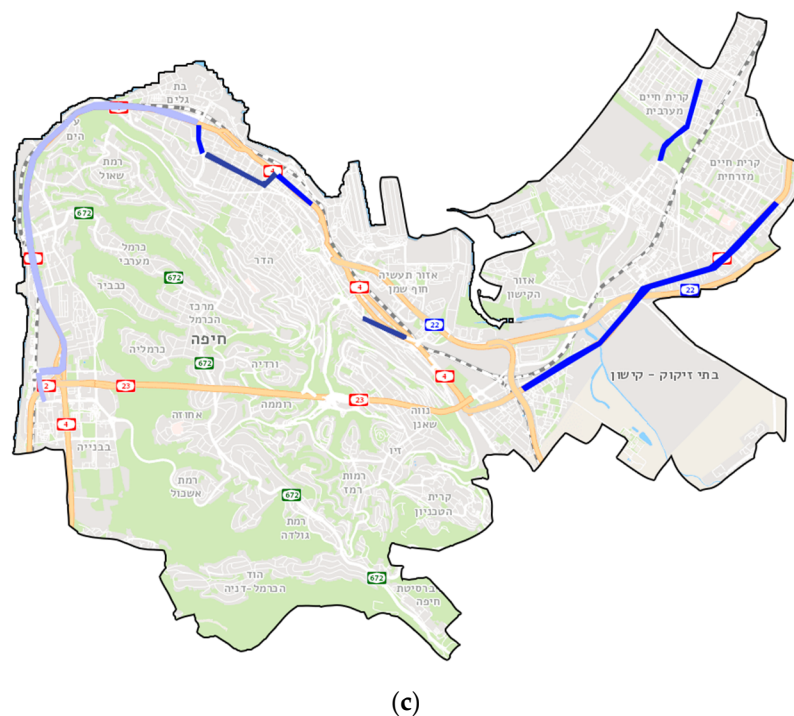


Figure A1. The case study maps: (a) Tel Aviv: the BPR is given in blue and comparison-group roads in red; (b) Jerusalem: the BPR is given in blue and comparison-group roads in red; (c) Haifa: the three groups of BPRs are given in different blue colors. The maps were produced using <https://www.govmap.gov.il/>. For Jerusalem, the municipality borders are not indicated.

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