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# A comparative evaluation of the safety performance of bus priority route configurations

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## Abstract

One way to promote public transport use in cities lies in establishing bus priority routes (BPRs) on main traffic arterials, to reduce bus travel times. But, BPRs require infrastructure changes in road layouts, creating more complex traffic settings that may have safety implications. Previous research indicated that design features affect BPRs' safety, but findings regarding the impacts of various BPR configurations are scarce. In this study, we examined the safety performance of three BPR configurations: barrier-separated central, open centre-lane and curbside BPRs, in Israel. Multivariate regression models were fitted to identify design features affecting accident occurrences on urban arterials with BPRs, using a database on all BPRs in operation. The comparative evaluations showed that barrier-separated BPRs were characterised by lower accident rates on road sections but by substantially higher accident numbers at junctions, relative to other BPR types, and particularly when bus-overtaking was possible. Hence, the use of barrier-separated bus routes should be reduced and bus-overtaking settings should be avoided, when implementing BPRs. In the comparison of curbside and center-lane BPRs none of them demonstrated a superior safety performance: the centre-lane BPRs were safer on sections while at junctions both types had advantages for certain accident types, thus, both forms are applicable in future BPR designs.

**Keywords** Public transport, Bus priority routes, Configuration, Safety performance, Accident model, Infrastructure, Urban roads

## 1 Introduction

Responding to increased urban density, traffic congestion and urban sprawl, modern policies of sustainable urban mobility promote the use of public transport, together with walking and cycling [29, 30, 42, 45]. Development of sustainable urban mobility plans is encouraged in European cities [35]. A shift to sustainable mobility is also expected to support the desired road safety

developments, as indicated by leading European and world organisations [1, 46].

One of the forms of public transport promotion lies in establishing bus priority systems on arterial streets in cities and suburban areas, while bus rapid transit (BRT) presents the ultimate form of such priority [9, 10, 24, 25]. Internationally, bus priority systems have been rapidly developing over recent decades, as a response to the needs for urban mobility [9, 25], and examples of such systems can nowadays be met in South- and North-American countries, as well as in India, Turkey, China, Australia. In Europe, there has been a long tradition of providing bus lanes and on-street bus priority control measures [36], while BRT systems are less common.

The state of bus systems in Europe was examined by a large group of European experts in a COST-project [13],

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which overviewed recent developments and considered in detail specific examples of bus systems from 14 countries. The project stated that bus systems in Europe need a recovery to play a more dominant role in public transport [22]. However, due to high density, narrow streets and mixed land uses in most European cities, the experience of North and Latin American BRT systems are not directly transferable and locally fitted solutions are needed. They suggested to term the domain as "Bus with a high level of service (BHLS)" systems [13] and argued that BHLS can be implemented in congested zones, such as city centers, and also on exclusive lanes of heavily-trafficked routes.

In Israel, over the past decades, government authorities have been promoting a policy of encouraging public transport in view of the growing problem of congestion in many urban areas, especially at the entrance to large cities [28, 32]. This policy has been manifested in establishing bus priority routes (BPRs), in various cities, with the allocation of transport infrastructure space for such routes. For example, in the Haifa metropolitan area, a BRT system called Matronit was built in 2006–2013 and launched in 2013 [17]; it is based on high-capacity articulated buses and covers some 40 km of bus priority streets and routes. In Tel-Aviv, there are more than 40 kms of BPRs, with various public transport lines and operators. Currently, hundreds of kilometres of BPRs are being planned and implemented throughout the country as part of a nation-wide program called "Rapid to the city" [28].

Establishing bus priority systems and setting BPRs are usually associated with mobility benefits, such as reducing travel time and increasing commercial speeds of buses during rush hours [7, 9, 23]. Such advantages were demonstrated, for example, in a study that accompanied the operation of a motorway shoulder bus-lane during rush hours in Israel [18] and, in many cases, were reported in operating dedicated bus lanes in and near European cities [13].

Moreover, from a strategic viewpoint, a relation can be shown between encouraging the use of public transport and better road safety. According to evaluations conducted in the USA, European countries, and Israel [12, 27, 34, 39], bus travel is safer than private vehicles' use, based on the estimation of casualty' or fatality rates per km-travelled by vehicle occupants. In addition, in the long term, a direct link is expected between the growth in use of public transport and the decline in the number of fatalities in road accidents per urban resident [27, 38]. Therefore, in terms of strategic transport policy, the improvement in bus systems can assist in promoting a shift from private cars to public transport, along with a decrease in road traffic injury, due to a decline in the

amount of traffic within the city and the higher level of safety of traveling on public transport.

At the same time, introducing BPRs on urban roads requires essential infrastructure changes in road layouts, by assigning lanes and other traffic settings for the exclusive or priority run of buses, to reduce bus travel times and improve public transport services [24, 25, 40]. Such infrastructure settings are typically more complex than traditional urban settings, which may lead to negative safety implications, as was observed in some cases (see Sec.2). Furthermore, most infrastructure solutions with regard to BPR settings, which are presented in the international practice, mainly rely on engineering judgment and not on formal safety evaluations, while previous knowledge of the comparative safety performance of various BPR configurations is inconsistent. This study aimed to reduce these gaps by producing new results based on safety evaluations of several BPR configurations, which are familiar in the international practice and applied on Israeli roads over the last decades.

From a practical perspective, the study aspired to provide empirical knowledge to support the selection of safety-preferable infrastructure solutions by designers of bus systems—to reduce accident risk under the BPR settings. The study findings can be relevant for European practice as well, due to the similarity in urban and traffic conditions between many European and Israeli cities, e.g. high traffic density and congestion in metropolitan and urban areas [29, 35], mixed land uses in many city districts [13] and presence of vulnerable road users [1], beside the need to provide public transport priority on urban roads.

## 2 Previous literature on safety impacts of bus priority systems and routes, and the study focus

Current findings around the world pertaining to the safety-related effects of bus priority systems and BPR settings are not extensive and sometimes contradictory. Studies that summarised the international experience on the topic noted that over the years less attention has been devoted to the implications of these systems on road safety than to other effects, such as their impacts on travel time, land value, or exhaust and greenhouse gas emissions [9, 10, 43]. In particular, knowledge is limited as to the ways in which various types of BPR settings affect the frequency and severity of road accidents [8, 10, 19, 43].

Several studies estimated general safety impacts of bus priority systems. Some of them found reductions in road accidents but others reported an increase following the introduction of such systems. For example, the operation of BRT systems in a number of South-American cities and India led to accident reductions in the range of

21–69% in injury accidents and of 50% in fatal accidents [10]. Similarly, in Melbourne, Australia, the implementation of bus priority settings was associated with an 18% reduction in total accidents [20]. In contrast, U.S. studies showed higher accident rates following the implementation of dedicated traffic arrangements for buses [9, 11]. An Israeli study found that signalized junctions with BPRs were associated with higher accident frequencies than similar junctions but without BPRs [16], i.e. the addition of BPR settings raised accident rates.

As mentioned above, a major contribution to understanding bus systems' development in Europe was made by Finn et al. [13], which examined 35 examples of BHLS systems from 14 countries. As an equivalent to full BRT systems, a few cases were indicated in Europe, e.g. BusVAO in Madrid, Trans-Val-de-Marne system of Greater Paris and TEOR in Rouen. However, numerous examples of "lite-BRT" applications were found, such as Blue Buses in Stockholm, the Lianes of Dijon in France, the Linea Alta Mobilita in Northern Italian cities as well as bus priority lanes in the Netherlands (in Amsterdam, Eindhoven), England (e.g. in London, Leeds, Bristol, Cambridge), Germany (Hamburg), Spain (Madrid, Castellón), etc., thus indicating the importance of the BPR domain for the European practice. In addition, further developments are expected, e.g., in France, over 20 additional BPR systems are planned for implementation [33], based on initial local experiences and having adapted the BRT concept to the French urban environment and "transportation culture" [13].

The study demonstrated a wide range of infrastructure solutions applied in the BHLS systems, and suggested that "there is no European environment in which BHLS cannot be deployed". Furthermore, it was concluded that the safety level of bus systems was higher in comparison to other transport modes, but noted that if the implementation was not accompanied by appropriate infrastructure settings, the safety of streets with bus traffic could be compromised [13]. Yet, the study did not succeed in collecting data for detailed safety evaluations of bus priority systems in Europe.

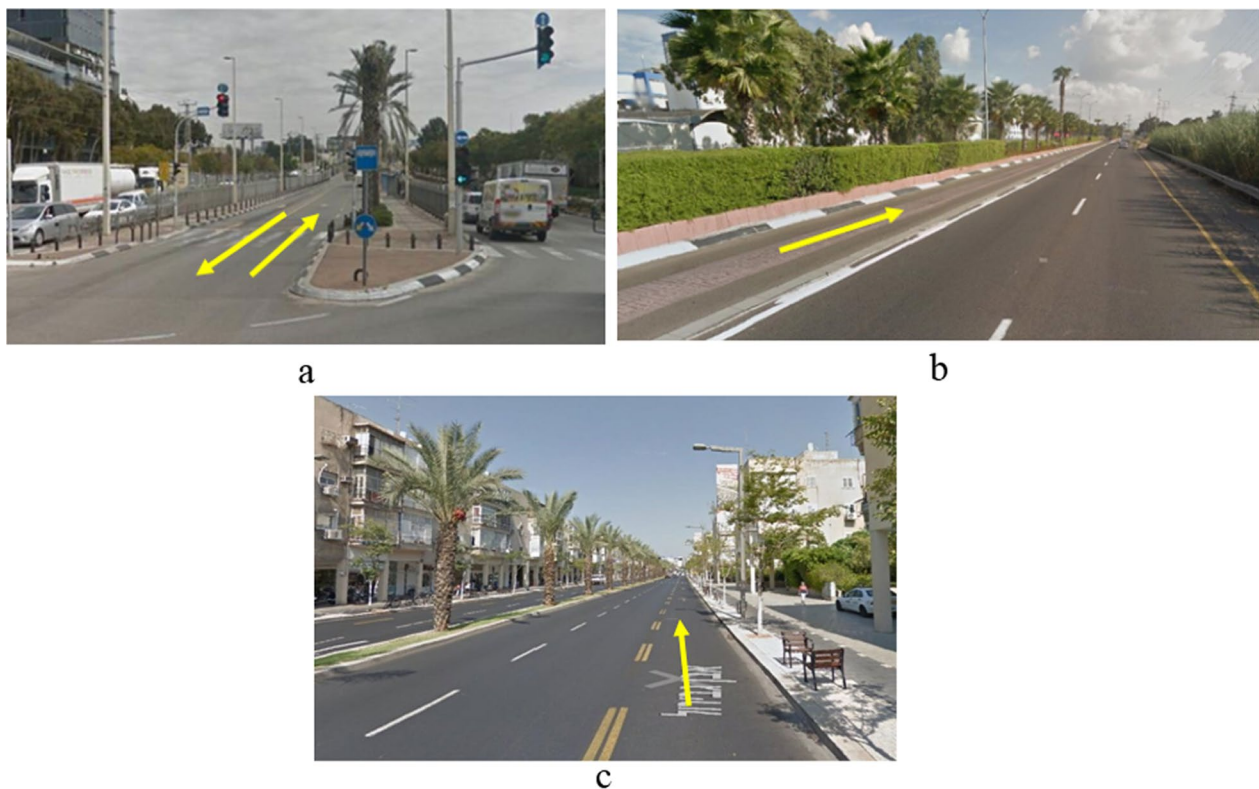
Concerning the bus priority systems' concepts and infrastructure solutions, certain similarity with light-rail transit (LRT) was indicated in the European practice and in general [10, 13, 14]. In addition, between bus and light-rail transit systems similar accident types and safety concerns were shown, with a focus on pedestrian safety [10]. Therefore, it is worth mentioning another European study [14], which summarized best practice experience in planning and operation of LRT in European cities, focusing on infrastructure solutions and safety risks. The study reported that various forms of LRT separation from other traffic are applied depending on the urban environment,

when the preference actually depends on the history and tradition of tramway systems in the country. Main safety principles were stated, and preferable measures were suggested to avoid safety hazards in interaction of tramway systems with other road users [14, 15]. However, as in the case of BHLS systems, most recommended infrastructure solutions relied on engineering judgment or common practices and not on formal safety evaluations.

A few studies reported on safety effects of BPR design features. The main forms of BPR configurations, as opposed to conventional mixed traffic, are centre-lane or median route, curbside lane and counter-flow lane [9, 24]. (Examples of centre-lane and curbside lane configurations can be seen in Fig. 1, b-c). Using data on vehicle and pedestrian accidents in BPR systems in several South-American cities, accident models were fitted and showed that centre-lane and curbside configurations were safer compared to counter-flow bus-lanes [8]. However, concerning the safety-related preference of a *centre-lane* BPR related to a curbside configuration, the summary of international literature did not provide unequivocal results [9]. The summary reported that presence of a median (as part of a centre-lane BPR) was associated with a reduction in road accidents [9]. A positive impact on road safety of centre-lane BPRs was found in repeated analyses of accident changes following the introduction of such systems in South-America and India [10]. However, evaluations in several Israeli cities showed that BPRs' implementation was associated with increasing trends in accident frequencies, for all forms of BPR configurations, while centre-lane BPRs were generally safer than curbside BPRs [19].

Regarding the safety impact of the *curbside* BPRs research findings differed, as well. For example, in Mexico, this configuration was associated with a significant increase in both vehicle and pedestrian accidents in one city and with insignificant impact in another [10]; in New York, the curbside lanes' introduction was associated with a significant increase in total accidents, vehicle collisions, and pedestrian accidents, on road sections [4]; in Hong Kong, the safety impacts of curbside lanes' setting were not statistically significant [41]. In contrast, in Australia following the establishment of BPRs, which were mainly in the form of curbside lanes, lower accident rates were found on the road sections with BPRs [20, 21].

Previous studies which examined statistical relations between the BPR characteristics and road accidents, also found that the number of accidents rises with the increase in the level of exposure, e.g. higher volume of vehicle traffic, greater bus frequency, higher density of bus stops [5, 21]. In addition, research findings indicated that a higher number of lanes for general traffic and a higher number of legs at the intersections, on the bus



**Fig. 1** BPR configurations: **a** barrier-separated central, **b** open centre-lane, **c** curbside. Note: arrows indicate the directions of bus traffic

routes, were associated with higher accident frequencies [8, 9].

Existing summaries of international literature and guidelines supply recommendations for reducing accident risks in bus priority systems [9, 24, 31, 40]. In particular, they suggest promoting traffic settings, such as: a physical separation of bus lanes from general traffic to prevent collisions with other vehicles; adding a raised median on the roads with BPRs; fencing along the bus corridors to prevent uncontrolled pedestrian crossings; using only signalized junctions; placing bus stops adjacent to junctions.

Over the last decades, in Israel, such features were encouraged in the BPR implementations. In practice, over the years, a *barrier-separated central* BPR configuration has become common, constituting a bus corridor situated in the centre of an urban arterial, which is physically separated from other vehicle lanes by fencing, and has signalized intersections only and bus stops adjacent to junctions (Fig. 1-a). (It should be noted that international literature, e.g. [7, 9, 10], does not suggest a common term for this type of BPR separation. This configuration definitely belongs to "segregated" BPRs according to [7], indicating a "dedicated carriageway" for bus traffic, whereas in other configurations the

bus lane shares carriageway with other traffic. Since in Israel this configuration always included a physical separation from other traffic in the form of steel fencing, we applied the term of "barrier-separated central" BPR.)

This configuration evidently adopts the international recommendations pertaining to BPRs' separation. However, road accidents continued to occur and evaluations showed that junctions with BPRs present hazardous locations, with multiple pedestrian accidents [16]. Traffic engineers claim that in terms of vehicle traffic, central BPR settings at junctions create additional conflict points, increase the junction size and prolong vehicle clearance times; consequently, the junction design becomes more complex, with a greater potential for road accidents. With respect to pedestrian movement, the change is quite dramatic, as pedestrians must cross a large number of traffic lanes, whereas in the case of a barrier-separated central BPR, there are three rather than two traffic routes to be crossed, leading to a substantial change in the rules of pedestrian behaviour when crossing the road (the so-called "three-route effect") [16]. An ordinary pedestrian, after having crossed the first route (with vehicle traffic approaching from the left), expects vehicles to come from the right, but then encounters



**Fig. 2** Example of barrier-separated central BPR with a possibility for bus-overtaking near a bus stop

a bus traffic coming from the left, again, as part of a bi-directional bus route. This means that a barrier-separated central BPR configuration rather disarrays pedestrians' road-crossing habits that may increase accident risk.

It should be noted in this context that evaluating other BPR configurations in Israel, the problem of pedestrian vulnerability at junctions was observed as well. For example, when monitoring the BRT system in Haifa during the first years of its operation, rising trends in pedestrian accidents were observed at junctions with curbside and centre-lane BPRs [17, 19].

Furthermore, in 2013–2014, several fatal accidents occurred at sites with barrier-separated central BPRs in one of Israeli cities (Petah Tikva), with numerous discussions held in the media and in the professional communities. Following these incidents, transport authorities raised questions concerning the safety level of barrier-separated BPRs related to other common BPR configurations, and future design preferences in planning BPRs, respectively. Therefore, it was decided to conduct a study, to examine the safety levels of barrier-separated BPRs as opposed to open centre-lane and curbside BPRs, under the local conditions. The study was also needed as previous literature did not reflect empirical findings that could support the safety preference among the BPR configurations.

### 3 Methodology

In this study, we conducted a comparative evaluation of safety performance of sites with three BPR configurations, namely: barrier-separated central, open centre-lane and curbside BPRs (Fig. 1a–c), based on the analysis of accident data.

#### 3.1 Data preparation

The study applied a detailed database that was collected by a team commissioned by the Ministry of Transport

(MOT), and included information on all roads with BPRs throughout the country that existed in urban areas in Israel, in 2015. The BPR locations were identified using city maps together with enquiries to the MOT regions and municipalities. For each traffic arterial with a BPR, a detailed list of the road junctions and sections was prepared. For each site, the road and traffic characteristics were defined, including: a BPR configuration; the type of area (i.e., the surrounding environment: urban or suburban); number of vehicle lanes on the route (in addition to the bus lanes); whether the BPR setting enabled buses to be overtaken near a bus stop; and the level of pedestrian activity at the site vicinity. As to the possibility of bus-overtaking near a bus stop, it is common for a curbside configuration (where an overtaking is possible through the adjacent lane) and can also be found on a barrier-separated central BPR, as is illustrated in Fig. 2. In the latter case, when a bay is available at the bus stop, a second bus approaching the bus stop can overtake the first bus that is already standing at the stop.

Furthermore, for all junctions, on each BPR arterial, efforts were made to collate information on traffic volumes of vehicles entering the junction, on the main and secondary roads, as well as on bus traffic on the main road (from the MOT and municipalities' traffic counts). The data on traffic volumes collected by various authorities were converted into a uniform scale (of 14 counting hours, 6 am–8 pm). The selection of road and traffic characteristics to be considered in the analysis, beside the main feature of a BPR configuration, relied on previous research which indicated the influence of such characteristics on accident occurrences on BPRs and urban roads, in general [8, 10, 11, 20, 21].

The accident data for roads with BPRs were collected for four years, 2010–2013,<sup>1</sup> based on the accident files of

<sup>1</sup> The database was prepared in 2015, when accident files were available until 2013.

the Central Bureau of Statistics (CBS). To identify accidents relevant to the BPR sites, a detailed list was prepared of the intersecting roads at each BPR junction and of the house numbers located on both sides of each road section with a BPR. If the house numbers were not identifiable for a certain road section, or whenever a specific junction could not be recognized among the CBS list of junctions (mainly due to the absence of name of secondary road), the site was removed from the analysis.

In total, data were collected on 26 arterial roads with BPRs located in nine cities. The initial lists of all the sites included 144 junctions and 126 road sections. After removing the unidentified sites in the CBS accident files, 137 junctions and 92 road sections remained in the database. The accident data were collected for five accident types, which are usually examined in the BPR context [8, 10, 17, 19], such as: total injury accidents and the subgroups of severe, pedestrian, and bus accidents and accidents involving buses and pedestrians.

For the analysis, the study database (both road sections and junctions) was converted into units of "site-year". This means that if a certain BPR site was in operation during the whole four-year period, four "observations" were produced in the study database, with different yearly accident frequencies (as observed each year). This conversion was required as some of the BPR sites did not exist during the whole four-year period of consideration, i.e. were in operation from one to three years, providing one to three "observations", respectively. Furthermore, it enabled us to account for fluctuations in annual accident numbers at the same sites (instead of using mean values) and fit explanatory models to yearly accident frequencies—a form, which is simple and more convenient for application by safety practitioners (compared to prediction of an average value across several years). In addition, being aware of non-uniformity of traffic counts provided by various authorities, several categories of traffic volumes were defined, from low to high.

### 3.2 Data analysis

The aim of the analysis was to estimate the safety level of road sites belonging to the BPR corridors, with a focus on the question of a difference between the safety levels of various BPR configurations. Moreover, the analysis should look into the impacts of other road and traffic characteristics of the BPR sites (as introduced above), to evaluate differences in safety performance of the BPR configurations having controlled for such characteristics.

Initially, correlations between potential explanatory variables were examined by using a Pearson chi-square test and phi-coefficient as a measure of association [26]. If pairs of highly-correlated characteristics were

recognized, one of the characteristics in each pair was omitted from further consideration. In addition, some characteristics were combined into "united" features, to avoid small numbers of observations in the categories submitted for accident modelling.

The accident analysis examined separately the safety levels of road sections and junctions. In each case, a multivariate Poisson or negative-binomial regression model was fitted to predict accident numbers per site per year and to identify design features affecting accident occurrences. In addition, random site effects were introduced in each model, to account for possible dependence among accident numbers at the same site in different years. In order to increase the power and parsimony of our models, we intended to model all accident types simultaneously, while enabling different impacts of explanatory variables on various accident types. Due to data limitations, this approach was only applicable to junction accidents, while, for road sections, separate models were adjusted to two accident types (see Sect. 4). The general model had the form:

$$\lambda_{ijk}|u_j = \exp(\beta x_{ijk} + u_j)$$

where  $\lambda_{ijk}$ —mean number of accidents of type  $k$  for observation in year  $i$  on site  $j$  (given  $u_j$ );  $\beta$ —vector of the estimable parameters;  $x_{ijk}$ —vector of the explanatory variables at year  $i$  on site  $j$  and accident type  $k$ ;  $u_j$ —a random effect of site  $j$ , which is a normally distributed term, with mean zero and variance  $\sigma_\alpha^2$ . The marginal mean is computed as  $\exp(\beta x_{ijk})$ , which equals the expected  $\lambda_{ijk}$  for average  $u_j$  (i.e.  $u_j = 0$ ). In the models for road sections, the logarithm of section length was used as an offset (i.e. its  $\beta$  coefficient was forced to be one), thus the models actually predict accident rates per km.

Model parameters were estimated by a maximum likelihood procedure, using *Adaptive Quadrature* as a computational approach to calculate integral approximation of the log-likelihood. In comparison to pseudo-likelihood methods, this method enables the use of likelihood ratio tests and information criteria, which are sensible, and the resulting estimates show a better asymptotic behavior and are less prone to small-sample bias. Model fitting was carried out using the GLIMMIX procedure of Statistical Analysis Software (SAS) [37], with the method QUAD. An assessment of the goodness-of-fit of the models was conducted using the Cox and Snell  $R^2$  [6], which is calculated as follows:

$$R^2 = 1 - \exp\left(\left(\frac{2}{N}\right) * (-0.5) * (LL(0) - LL(\beta))\right)$$

**Table 1** Descriptive statistics of the study database on road sections\*

Characteristic ( <i>variable in the models</i> )	Statistics: <i>categories with percent distribution; mean and sd for numeric values; for accidents—frequencies per site with percent distribution</i>
Type of BPR configuration ( <i>BPR type</i> )	(1) curbside—66%, (2) open center-lane—20%, (3) barrier-separated central—14%
Type of area combined with number of lanes for general traffic ( <i>Area</i> )	(0) urban, 1 lane—14.6%, (1) urban, 2–3 lanes—74.7%, (2) suburban, 2–3 lanes—10.7%
Year of accident occurrences ( <i>Year</i> )	(1) 2010—24%, (2) 2011—24%, (3) 2012—26%, (4) 2013—26%
Section length, km (offset in the models)	Mean 0.33, sd 0.30, min 0.05, max 2.02
Vehicle traffic, in ten thousands ( <i>V_veh</i> )	Mean 3.8, sd 1.5, min 1.2, max 7.8
Categories of vehicle traffic, in ten thousands ( <i>Cat_veh</i> )	(1) up to 2—14%, (2) between 2–3—16%, (3) between 3–4—30%, (4) over 4—40%
Bus traffic, in thousands ( <i>V_bus</i> )	Mean 1.6, sd 0.5, min 0.4, max 2.5
Categories of bus traffic, in thousands ( <i>Cat_bus</i> )	(1) up to 1—18%, (2) between 1–1.5—26%, (3) between 1.5–2—24%, (4) over 2—31%
Total injury accidents	0–85.1%, 1–8.1%, 2–3.7%, 3 or more—3.1%
Severe accidents	0–96.1%, 1–2.8%, 2–0.8%, 3–0.3%
Pedestrian accidents	0–93.0%, 1–6.7%, 2–0.3%
Bus accidents	0–96.9%, 1–3.1%
Bus & pedestrian accidents	0–98.0%, 1–2.0%

\*N = 356. Vehicle and bus traffic volumes—per 14 h of day

where  $LL(\beta)$  is the log-likelihood at convergence;  $LL(0)$  is the log-likelihood with only the constant term; N—the sample size. Moreover, for testing the superiority of the target model, a likelihood ratio test comparing the log-likelihood values between two competing models was conducted, as follows:

$$\chi^2 = -2 * [LL(\beta_A) - LL(\beta_B)]$$

where  $LL(\beta_A)$  and  $LL(\beta_B)$  are the log-likelihood at convergence for model A (with intercept and random effects only) and model B (with fixed effects added), respectively. The  $\chi^2$ -statistic is chi-square distributed with the degrees of freedom equal to the difference in the number of parameters in two models [2]; it enables to estimate the significance of difference between the models.

Using the models, post hoc pairwise comparisons were conducted to estimate differences in accident means at sites with certain types of BPR configurations. For that, we applied least-squares means differences with a Bonferroni adjustment to control for multiple comparisons [3]. When multiple hypotheses are tested on the same dataset, the probability of observing a rare event increases, and therefore, the likelihood of rejecting a null hypothesis incorrectly (making a Type I error) increases. Hence, the probability of rejecting the null hypotheses should be corrected. One of the p-value adjustment methods to control the overall Type I error rate for multiple comparisons is a Bonferroni adjustment, which can be applied using the SAS software [37].

## 4 Results

### 4.1 Models for accidents on road sections with BPRs

The study database on road sections with BPRs included 92 sites, with 356 observations ("site-year", as was introduced in Sec.3.1); its descriptive statistics is presented in Table 1. In total, on the study road sections occurred: 99 injury accidents, of which 19 were severe, 26 involved a pedestrian, 11 involved a bus, 7 were with a bus and a pedestrian. A preliminary analysis revealed high correlations between the features of type of BPR configuration and the possibility for bus-overtaking (phi-coefficient 0.96,  $p < 0.0001$ ), and also between the type of area and the level of pedestrian activity (phi-coefficient 0.90,  $p < 0.0001$ ). The section data showed that the bus-overtaking feature was pertinent mostly to a curbside configuration, and that a high level of pedestrian activity was in urban areas while low level—in suburban areas. Thus, the number of potential explanatory variables was shortened (second feature in each pair above was omitted from further analysis). In addition, the characteristics of the type of area and the number of lanes for general traffic were combined, providing three final categories (see Table 1).

As severe and bus accidents on the road sections were rare (in 96–97% of road sections no such accidents occurred, see Table 1), only models for pedestrian and total injury accidents were attempted. For each accident type, several models were adjusted, with the design features as presented in Table 1 and applying various definitions of traffic volumes, such as: no use of

**Table 2** Poisson regression models fitted to total injury accidents on road sections with BPRs

<b>(a) Model 1—no use of traffic volumes</b>					
Variables	Estimate	Standard error	DF	t Value	Pr> t
Intercept	− 1.53	1.08	87	− 1.41	0.162
BPR type: curbside	2.56	1.06	264	2.41	0.017
BPR type: open center-lane	1.00	1.08	264	0.93	0.355
BPR type: barrier-separated central	0				
Area: urban, 2–3 lanes	− 1.55	0.73	264	− 2.11	0.036
Area: suburban	− 0.43	0.73	264	− 0.59	0.554
Area: urban, 1 lane	0				
<b>(b) Model 2—with continuous traffic volumes</b>					
Variables	Estimate	Standard error	DF	t Value	Pr> t
Intercept	− 1.76	1.11	85	− 1.58	0.117
BPR type: curbside	2.49	1.07	264	2.34	0.020
BPR type: open center-lane	1.03	1.08	264	0.96	0.340
BPR type: barrier-separated central	0				
Area: urban, 2–3 lanes	− 1.74	0.77	264	− 2.26	0.025
Area: suburban	− 0.79	0.82	264	− 0.96	0.337
Area: urban, 1 lane	0				
log (V_Bus)	− 0.23	0.38	264	− 0.60	0.547
log (V_Veh)	0.44	0.48	264	0.92	0.360
<b>(c) Model 3—with categorical traffic volumes</b>					
Variables	Estimate	Standard error	DF	t Value	Pr> t
Intercept	− 1.11	1.53	81	− 0.73	0.470
BPR type: curbside	2.45	1.06	261	2.31	0.022
BPR type: open center-lane	0.93	1.08	261	0.87	0.387
BPR type: barrier-separated central	0				
Area: Urban, 2–3 lanes	− 2.00	1.14	261	− 1.76	0.080
Area: Suburban	− 1.10	1.17	261	− 0.94	0.347
Area: Urban, 1 lane	0				
Year: 1	0.66	0.29	261	2.31	0.022
Year: 2	0.51	0.29	261	1.72	0.087
Year: 3	− 0.24	0.35	261	− 0.69	0.494
Year: 4	0				
Cat_veh: 1	− 0.96	1.11	261	− 0.86	0.391
Cat_veh: 2	− 0.41	0.57	261	− 0.72	0.471
Cat_veh: 3	− 0.33	0.45	261	− 0.73	0.465
Cat_veh: 4	0				
Cat_bus: 1	− 0.18	0.44	261	− 0.40	0.687
Cat_bus: 2	0.45	0.40	261	1.14	0.254
Cat_bus: 3	− 0.10	0.37	261	− 0.28	0.776
Cat_bus: 4	0				

(a) Model fit statistics: − 2 Log Likelihood = 361.95; AIC = 373.95; R<sup>2</sup> = 15.1%. Likelihood ratio test:  $p < 0.0001$ . Type III Tests of fixed effects: for BRT type  $p < 0.01$ ; for Area  $p < 0.0001$ .

(b) Model fit statistics: − 2 Log Likelihood = 361.18; AIC = 375.18; R<sup>2</sup> = 15.2%. Likelihood ratio test:  $p < 0.0001$ . Type III Tests of fixed effects: for BRT type  $p < 0.05$ ; for Area  $p < 0.001$ . log—logarithm.

(c) Model fit statistics: − 2 Log Likelihood = 342.92; AIC = 370.92; R<sup>2</sup> = 19.5%. Likelihood ratio test:  $p < 0.0005$ . Type III Tests of fixed effects: for BRT type, Area, Year  $p < 0.05$ ; for Cat\_veh  $p = 0.77$ , for Cat\_bus  $p = 0.11$ .



**Table 3** Results of pairwise comparisons between injury accident means on road sections with various BPR configurations

BPR configuration* (TypeX)	Compared to BPR configuration* (TypeY)	Model 1			Model 2			Model 3		
		Estimate	St. error	Adj P	Estimate	St. error	Adj P	Estimate	St. error	Adj P
1	2	1.56	0.63	0.041 <sup>##</sup>	1.47	0.64	0.067 <sup>#</sup>	1.52	0.65	0.059 <sup>#</sup>
1	3	2.56	1.06	0.050 <sup>#</sup>	2.49	1.07	0.061 <sup>#</sup>	2.45	1.06	0.065 <sup>#</sup>
2	3	1.00	1.08	1.0	1.03	1.08	1.0	0.93	1.08	1.0

\* See categories of BPR configuration in Table 1. Significant difference with <sup>##</sup> $p < 0.05$ , <sup>#</sup> $p < 0.1$

volumes, continuous volumes, and categorical volumes. The models fitted to pedestrian accidents showed insignificant effects for the design features and negligible values of  $R^2$ , and hence were disregarded.

The models adjusted for total injury accidents are presented in Table 2; Poisson models were used. The goodness-of-fit of the models ranged from 15% to 19.5% and was higher when the categorical values of traffic volumes were applied.<sup>2</sup> (The likelihood ratio tests were significant for all the models, with  $p < 0.001$ .) All the models were consistent in showing significant effects for the type of BPR configuration and the type of area (combined with the number of lanes for general traffic), while the effects of vehicle traffic and of bus traffic were insignificant.

Based on the models, Table 3 presents the results of the pairwise comparisons between the total accident means on road sections with various BPR configurations (see definitions in Table 1). The "estimate" in Table 3 corresponds to the difference in log-expected accident frequency at "TypeX" configuration related to "TypeY" configuration, while controlling for other site characteristics. If the "estimate" is positive and significant, the accident rate in the first case (TypeX) is higher than in the second case (TypeY), and vice versa. In addition, Fig. 3 illustrates the least-squares means of accident rates by the BPR configurations (which are estimates of the marginal means over a balanced population).

The model results showed consistently that higher accident frequencies were expected on road sections with a curbside BPR configuration relative to centre-lane and barrier-separated BPRs, while the differences in accident means between the open centre-lane and barrier-separated configurations were insignificant. Yet, it can be noted (see Fig. 3) that, on road sections, barrier-separated BPRs were characterized by lowest values of accident rates in comparison to other BPR configurations.

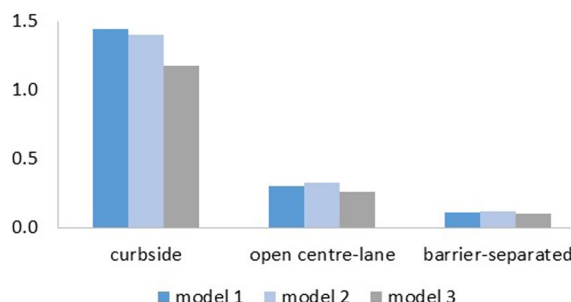
In addition, pairwise comparisons indicated that on BPR road sections with multiple lanes for general

traffic fewer accidents are expected when sections are situated in an urban environment as opposed to suburban one (for example, with  $p < 0.001$ , based on Model 1 in Table 2). This finding can be related to higher travel speeds and more substantial traffic volumes in suburban areas that lead to higher accident rates.

**4.2 Models for accidents at junctions with BPRs**

The database of junctions with BPRs included 137 sites, with 519 observations ("site-year"); its descriptive statistics is shown in Table 4. At the study junctions occurred, in total: 816 injury accidents, of which 108 were severe, 206 with a pedestrian, 103 with a bus, 55—with a bus and a pedestrian. A comparison with the numbers of section accidents indicated consistently that 85–90% of accidents, of all types considered, occurred at the BPR junctions.

Following the preliminary analysis of data frequencies, the features of BPR configuration and the possibility for bus-overtaking were combined, providing four united categories; similarly, the characteristics of the type of area, the number of lanes for general traffic and the level of pedestrian activity were combined, composing four final categories (see Table 4). The junction characteristics included in the accident model development comprised the design features as well as the categories of vehicle traffic, on the main and secondary roads, and of bus traffic. As mentioned above, at junctions, more accidents



**Fig. 3** Least-squares means of injury accident rates\* on road sections by BPR configuration. (See models in Table 2). \*Accident number per km, per year

<sup>2</sup> With categorical volumes, two models were fitted, without and with adding a year among the explanatory variables. The model with year is shown in Table 2.

**Table 4** Descriptive statistics of the study database on junctions\*

Characteristic ( <i>variable in the model</i> )	Statistics: <i>categories with percent distribution; mean and sd for numeric values; for accidents—frequencies per site with percent distribution</i>
Type of BPR configuration combined with bus-overtaking possibility ( <i>BPR type_Bus_over</i> )	(1) curbside—57%; (2) open center-lane—17%; (30) barrier-separated central and no bus-overtaking—20%; (31) barrier-separated central with bus-overtaking—6%
Type of area combined with number of lanes for general traffic and with level of pedestrian activity ( <i>avp</i> )	(001) urban, 1 lane, high—12%; (010) urban, 2–3 lanes, low—6%; (011) urban, 2–3 lanes, high—67%; (110) suburban, 2–3 lanes, low—15%
Year of accident occurrences ( <i>Year</i> )	(1) 2010—23%, (2) 2011—25%, (3) 2012—26%, (4) 2013—26%
Vehicle traffic on main road, in ten thousands	Mean 3.0, sd 1.3, min 0.4, max 5.9
Vehicle traffic on secondary road, in ten thousands	Mean 2.1, sd 1.7, min 0.1, max 8.5
Categories of vehicle traffic on main road, in ten thousands ( <i>Cat_veh_main</i> )	(1) up to 2—22%, (2) between 2–3—26%, (3) between 3–4—29%, (4) over 4—23%
Categories of vehicle traffic on secondary road, in ten thousands ( <i>Cat_veh_sec</i> )	(1) up to 2—25%, (2) between 2–3—37%, (3) between 3–4—26%, (4) over 4—12%
Bus traffic, in thousands	Mean 1.4, sd 0.6, min 0.2, max 3.9
Categories of bus traffic, in thousands ( <i>Cat_bus</i> )	(1) up to 1—26%, (2) between 1–1.5—30%, (3) between 1.5–2—26%, (4) over 2—18%
1—Total injury accidents	0—42.2%, 1—20.2%, 2—13.5%, 3 or more—24.1%
2—Severe accidents	0—83.0%, 1—13.5%, 2—3.1%, 3—0.4%
3—Pedestrian accidents	0—74.0%, 1—16.2%, 2—7.3%, 3 or more—2.5%
4—Bus accidents	0—85.5%, 1—11.0%, 2—2.7%, 3 or more—0.8%
5—Bus & pedestrian accidents	0—91.7%, 1—6.9%, 2—1.0%, more—0.4%

\*N = 519. Vehicle and bus traffic volumes—per 14 h of day

occurred than on the road sections, and the share of sites with no accident occurrences was lower (see Table 4), therefore, the analysis referred to all accident types. All accidents types were modelled simultaneously, and non-significant interactions were dropped from the model. A Negative-binomial regression model was fitted to the data. (The goodness-of-fit of the model was 34.5%, higher than in the models for road sections; the likelihood ratio test was significant).

The final model for accidents at junctions with BPRs (Table 5) showed significant fixed effects ( $p < 0.0001$ ) for accident type, type of BPR configuration (combined with a bus-overtaking), the interaction of accident type and BPR configuration, and vehicle traffic on the secondary roads. In addition, significant effects ( $p < 0.05$ ) were observed for year (of accident occurrence) and the level of bus traffic, while for the type of area (combined with the number of lanes and the level of pedestrian activity) and for vehicle traffic on the main roads the effects were insignificant.

Based on the model, pairwise comparisons between the accident means at junctions with various BPR configurations (combined with a bus-overtaking possibility, see definitions in Table 4), were estimated for each accident type (Table 6). The differences in accident means showed that, for all accident types, barrier-separated BPRs were associated with higher accident numbers than other BPR types, while for total accidents as well as for severe and

pedestrian accidents this effect was mainly related to the possibility of bus-overtaking at the bus stops. In the case of bus accidents and bus and pedestrian involving accidents, higher numbers were consistently expected at junctions with barrier-separated than with curbside BPRs, regardless the feature of bus-overtaking at the bus stops.

In terms of predicted accident means at junctions (Fig. 4), among the BPR types, the lowest numbers of total and severe accidents were expected for a centre-lane configuration, the lowest numbers of bus and bus-pedestrian accidents—for curbside BPRs, while for pedestrian accidents similar accident means were estimated for centre-lane and curbside configurations. For all accident types, much higher values were predicted for barrier-separated bus routes.

In addition, according to the model results, at BPR junctions, higher accident numbers were expected for higher traffic volumes on secondary roads, more specifically—at sites with traffic volumes over 10 thousands of vehicles per day as opposed to sites with traffic volumes below this value ( $p < 0.001$  in pairwise comparisons between category 1 and all other categories). The least-squares means of accident numbers by categories of bus traffic indicated, also, that higher accident frequencies were associated with higher bus traffic (but pairwise comparisons did not show significant differences between the categories).

**Table 5** Negative-binomial regression model for accidents at junctions with BPRs

Variables	Estimate	Standard error	DF	t Value	Pr> t
Intercept	0.01	0.64	121	0.01	0.994
Acc_type: 1	1.94	0.35	2439	5.52	<0.0001
Acc_type: 2	0.04	0.44	2439	0.08	0.934
Acc_type: 3	0.60	0.40	2439	1.51	0.132
Acc_type: 4	0.67	0.39	2439	1.72	0.085
Acc_type: 5	0				
BPR type_Bus_over: 1	-3.45	0.57	2439	-6.07	<0.0001
BPR type_Bus_over: 2	-2.31	0.69	2439	-3.35	0.001
BPR type_Bus_over: 30	-1.20	0.55	2439	-2.17	0.030
BPR type_Bus_over: 31	0				
Acc_type*BPR type_Bus_over: 1,1	1.95	0.48	2439	4.10	<0.0001
Acc_type*BPR type_Bus_over: 1,2	0.52	0.56	2439	0.94	0.349
Acc_type*BPR type_Bus_over: 1,30	0.04	0.41	2439	0.09	0.925
Acc_type*BPR type_Bus_over: 1,31	0				
Acc_type*BPR type_Bus_over: 2,1	1.80	0.56	2439	3.23	0.001
Acc_type*BPR type_Bus_over: 2,2	-0.04	0.73	2439	-0.06	0.954
Acc_type*BPR type_Bus_over: 2,30	-0.03	0.52	2439	-0.05	0.959
Acc_type*BPR type_Bus_over: 2,31	0				
Acc_type*BPR type_Bus_over: 3,1	1.77	0.52	2439	3.41	0.001
Acc_type*BPR type_Bus_over: 3,2	0.55	0.62	2439	0.89	0.376
Acc_type*BPR type_Bus_over: 3,30	0.18	0.47	2439	0.40	0.692
Acc_type*BPR type_Bus_over: 3,31	0				
Acc_type*BPR type_Bus_over: 4,1	0.32	0.54	2439	0.59	0.554
Acc_type*BPR type_Bus_over: 4,2	0.18	0.63	2439	0.28	0.779
Acc_type*BPR type_Bus_over: 4,30	-0.30	0.47	2439	-0.64	0.525
Acc_type*BPR type_Bus_over: 4,31	0				
Acc_type*BPR type_Bus_over: 5,1	0				
Acc_type*BPR type_Bus_over: 5,2	0				
Acc_type*BPR type_Bus_over: 5,30	0				
Acc_type*BPR type_Bus_over: 5,31	0				
avp: 001	0.45	0.50	2439	0.89	0.371
avp: 010	0.51	0.46	2439	1.11	0.268
avp: 011	-0.18	0.29	2439	-0.62	0.533
avp: 110	0				
Year: 1	0.03	0.09	2439	0.27	0.784
Year: 2	-0.18	0.09	2439	-1.88	0.060
Year: 3	0.12	0.09	2439	1.40	0.162
Year: 4	0				
Cat_veh_main: 1	0.04	0.38	2439	0.10	0.924
Cat_veh_main: 2	0.03	0.29	2439	0.10	0.916
Cat_veh_main: 3	0.37	0.25	2439	1.50	0.134
Cat_veh_main: 4	0				
Cat_veh_sec: 1	-1.36	0.34	2439	-4.00	<0.0001
Cat_veh_sec: 2	-0.15	0.29	2439	-0.53	0.597
Cat_veh_sec: 3	-0.14	0.32	2439	-0.46	0.648
Cat_veh_sec: 4	0				
Cat_bus: 1	-0.23	0.29	2439	-0.79	0.427
Cat_bus: 2	-0.67	0.32	2439	-2.12	0.034
Cat_bus: 3	0.06	0.26	2439	0.23	0.819
Cat_bus: 4	0				

Acc\_type presents accident types; see Table 4 for variable definitions. Model fit statistics: Pearson Chi-Square/DF = 0.78;  $R^2 = 34.5\%$ . Likelihood ratio test:  $p < 0.0001$ .

### 5 Discussion

In line with the modern policy of promoting public transport use in cities [29, 35] and being aware of possible negative safety impacts of introducing bus priority settings on urban roads [4, 10, 16], this study aspired to

compare the safety performance of urban arterials with three BPR configurations, which are: barrier-separated central, open centre-lane and curbside bus routes. This issue was not explicitly examined by previous research [8–11], although these configurations are common in the

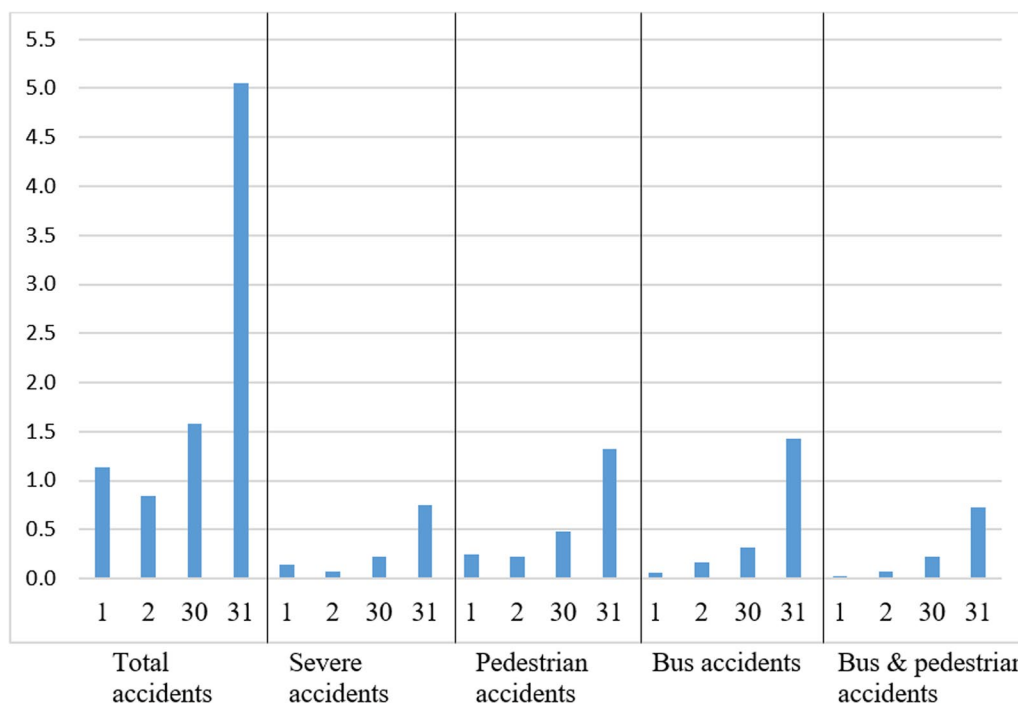
**Table 6** Results of pairwise comparisons between accident means at junctions with various BPR configurations

BPR configuration* (TypeX)	Compared to BPR configuration* (TypeY)	Total injury accidents			Severe accidents			Pedestrian accidents		
		Estimate	St. error	Adj P	Estimate	St. error	Adj P	Estimate	St. error	Adj P
1	2	0.29	0.36	1.0	0.70	0.55	1.0	0.08	0.42	1.0
1	30	-0.33	0.29	1.0	-0.42	0.36	1.0	-0.66	0.33	0.257
1	31	-1.49	0.39	0.001 <sup>#</sup>	-1.64	0.49	0.005 <sup>#</sup>	-1.67	0.44	0.001 <sup>#</sup>
2	30	-0.62	0.36	0.511	-1.12	0.56	0.281	-0.74	0.43	0.497
2	31	-1.78	0.50	0.002 <sup>#</sup>	-2.35	0.69	0.004 <sup>#</sup>	-1.76	0.57	0.012 <sup>##</sup>
30	31	-1.16	0.45	0.056 <sup>&amp;</sup>	-1.23	0.55	0.157	-1.02	0.50	0.248

BPR configuration* (TypeX)	Compared to BPR configuration* (TypeY)	Bus accidents			Bus & pedestrian accidents		
		Estimate	St. error	Adj P	Estimate	St. error	Adj P
1	2	-0.99	0.47	0.211	-1.14	0.62	0.392
1	30	-1.63	0.38	0.0001 <sup>#</sup>	-2.25	0.47	<0.0001 <sup>#</sup>
1	31	-3.13	0.47	<0.0001 <sup>#</sup>	-3.45	0.57	<0.0001 <sup>#</sup>
2	30	-0.63	0.46	1.0	-1.11	0.56	0.298
2	31	-2.13	0.58	0.002 <sup>#</sup>	-2.31	0.69	0.005 <sup>#</sup>
30	31	-1.50	0.50	0.017 <sup>##</sup>	-1.20	0.55	0.180

\* See categories of BPR configuration combined with bus-overtaking possibility in Table 4. Significant difference with <sup>#</sup> $p < 0.01$ , <sup>##</sup> $p < 0.05$ , <sup>&</sup> $p < 0.1$



**Fig. 4** Least-squares means of accident frequencies\* at junctions by accident type and BPR configuration. BPR configurations: 1—curbside; 2—open centre-lane; 30—barrier-separated, no bus-overtaking; 31—barrier-separated, with possibility for bus-overtaking. \*Accident number per site, per year

international practice of public transport priority routes in various countries [9, 13, 14]. The topic was particularly acute for local conditions in Israel where such configurations became typical in the past decades. Specifically, the barrier-separated BPR configuration, which reflected the preferable infrastructure solution of physically-separated bus routes, according to the international experience [9, 24, 40], but was characterized by fatal pedestrian accidents in the local practice, needed attention. Thus, detailed safety comparisons between the three BPR configurations were necessary to decide on their suitability for future BPR designs.

The study applied a comprehensive database, which included all the sites with BPRs that were in operation in the country (in 2015). Multivariate regression models were adjusted to evaluate accident frequencies and, consequently, to examine differences in safety performance of road sites with various BPR configurations, while controlling for other road and traffic characteristics. The results showed that, on road sections, the barrier-separated BPR configuration had safety advantages over two other BPR forms and, particularly, over the curbside configuration, while at junctions, it exhibited a poorer safety level relative to other BPR types. However, it should be noted that in all accident types, a statistically-significant worse safety performance of the barrier-separated BPRs was found in the case of presence of a bus-overtaking possibility near the bus stops, while the barrier-separated BPR without a possibility for bus-overtaking had a significantly poorer safety performance in the cases of bus accidents and accidents with buses and pedestrians, only. One can assume that infrastructure settings with a possibility for bus-overtaking in the barrier-separated BPRs, lead to higher bus speeds in the bus corridors thus increasing accident risk at junctions. Therefore, due to safety concerns, such BPR settings should be avoided.

The safety level of junctions with barrier-separated BPRs was consistently lower than the safety level of junctions with curbside BPRs, which presumably reflects the much higher complexity of signalized junctions with barrier-separated BPRs. The latter related to the higher number of carriageways on the road, additional conflict points for turning movements, a bigger junction size and longer clearance times, which overall lead to negative safety implications. Furthermore, the "three route effect" dictating changes in the traditional pedestrian crossing behaviour [16], cannot be ignored in this context, since a certain share of pedestrians in urban areas cross on red. Hence, other forms of BPRs than barrier-separation should be preferred, to reduce accident risks at junctions. For example, a better solution can be to use an open centre-lane BPR, removing the physical separation between the bus lane and general traffic lanes and leaving two

carriageways only to be crossed by pedestrians, at junctions. To note, such solutions are currently preferred in the design practice of median BPRs in Israel, but their safety impacts have yet to be evaluated. Another direction in seeking alternative junction designs for central BPRs can be in "traffic calming", e.g. by reducing general traffic lanes or turning movements at a junction, which were associated with positive safety effects in BPR operations [9, 19].

The suggested restriction on the use of barrier-separated BPRs is also supported by the finding that the majority of accidents on urban roads with BPRs, in all accident types considered by the study, occurred at junctions (85–90%). Thus, in spite of the advantage of the barrier-separated BPRs on road sections, since their safety records at junctions were worse compared to other BPR configurations, the overall safety performance of this BPR type can be judged as poorer relative to other BPR types. Yet, a reservation is needed at this point, since the current study did not conduct a safety evaluation of the whole BPR routes, as was done for example in South-American cities [10]; such an evaluation would be useful in the future, to delve into the differences in safety performance of various BPR types.

Concerning the preference in safety performance between the curbside and centre-lane BPRs, the current study did not provide an indubitable answer, similar to previous research [8, 10, 17]. The centre-lane configuration was much safer on road sections than curbside BPRs (a significant difference), while at junctions both configurations demonstrated some advantages (i.e. lowest accident frequencies), for certain accident types (but the differences in accident numbers were insignificant). The lowest frequencies of bus-involving accidents as associated with curbside BPRs probably indicate in favour of simpler traffic arrangements at urban junctions, which resemble conventional traffic settings (without BPRs). At the same time, the centre-lane BPR configuration was characterised by the lowest mean of severe accidents and thus, it may be considered as a preferable solution for urban areas since it better supports the targets of the safe-systems approach [1, 46]. Furthermore, both BPR forms were characterised by similar means of pedestrian accidents, whereas pedestrian injury is the main concern of BPR operation and bus transit systems, in general [8–10, 19, 30, 31]. Thus, it follows that both BPR configurations are suitable for application in the future planning of BPRs.

The study results can be useful for European practice, where BHLS systems are considered as an important means for promoting a shift to public transport use and are being re-established [13]. Due to certain similarity in traffic density and mixed land uses in urban areas in

Israel and European cities, the Israeli experience of urban roads' renovation to incorporate BPRs may be helpful for some European cases. The European study [13] indicated difficulty to set up design rules for bus priority systems, as more experience and evidence are needed in the field. Thus, the current study findings may provide some insights with regard to BPR infrastructure solutions with a particular focus on safety impacts, which were not yet estimated in Europe.

The study models indicated that more accidents are expected at BPR junctions with higher vehicle traffic and higher bus frequencies, which is consistent with previous research [5, 21]. The impacts of other design features, e.g. the number of lanes for general traffic or the number of legs at junctions, were not ascertained by the current study due to the limitations in the study data.

In spite of the efforts invested in the data collection (which as we mentioned comprised all the BPR roads throughout the country), the study analysis was limited by the available site samples, which were insufficient to explore safety impacts of various combinations of road and traffic characteristics of the BPR sites. In the future, it would be appropriate to conduct further research, in this direction, and especially, to examine the safety effects of more detailed infrastructure solutions, which are common on certain BPR configurations. Similarly, the safety impacts of BPR settings should be more thoroughly explored in the context of various levels of vehicle traffic, bus traffic and pedestrian activities, to provide a more solid basis for selecting practical solutions, while planning BPRs in cities.

## 6 Conclusions

In this study, statistical models were developed to evaluate accident frequencies on urban arterials with dedicated bus routes, while examining three bus route configurations, i.e. barrier-separated central, open centre-lane or curbside BPRs. The study applied the specially-collected database, which comprised all road sections and junctions with such BPRs that were present on the Israeli urban road networks.

The comparative evaluations showed that barrier-separated BPRs were characterised by lower accident rates on road sections but by substantially higher accident numbers at junctions, relative to other types of the BPRs, and particularly when bus-overtaking was possible. Hence, the use of barrier-separated BPRs should be reduced and bus-overtaking settings should be avoided, when implementing bus priority routes in the country. In the comparison of curbside and center-lane BPRs none of them

demonstrated a superior safety performance: the centre-lane routes were safer on sections while at junctions both configurations had advantages for certain accident types. Therefore, both forms can be judged as applicable in future BPR designs. A similar conclusion was drawn, under the local conditions, having monitored the safety performance of various BPRs in the newly established BRT system in the north of the country [17, 19].

The study enriches the international knowledge on the safety performance of various BPR configurations [8–10, 17, 19, 20], supporting the use of the centre-lane and curbside forms of BPRs and suggesting to restrict the application of barrier-separated bus routes. However, the preference of a specific BPR form can be case-sensitive, depending of the road environment, the role of the road considered in the urban road network and respective vehicle traffic volumes, current modal split in the city, strictness of the local policy for promoting active travel modes, etc.

The practice shows that BPR planners seek detailed answers to the safety implications of various traffic settings on the bus corridors, while existing knowledge on the topic is not extensive [9, 10, 43]. Thus, further research is still needed to provide a better understanding of safety impacts of infrastructure design solutions for BPRs, under various traffic and road conditions. Specifically, great interest would be in studies of European bus priority systems, for which safety evaluations are generally unavailable. The key issue can be seen in finding the right balance between mobility and safety needs, by integrating safety in public transport planning and operation, and promoting safer urban roads by design [1, 44].

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### Author contribution

All authors read and approved the final manuscript.

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### Availability of data and materials

The database collected in this study can be provided upon request.

### Declarations

#### Competing interests

The authors declare that they have no competing interests.

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