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ORIGINAL ARTICLE

International transferability of macro-level safety performance functions: a case study of the United States and Italy

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Abstract

Safety performance functions (SPFs), or crash-prediction models, have played an important role in identifying the factors contributing to crashes, predicting crash counts and identifying hotspots. Since a great deal of time and effort is needed to estimate an SPF, previous studies have sought to determine the transferability of particular SPFs; that is, the extent to which they can be applied to data from other regions. Although many efforts have been made to examine micro-level SPF transferability, few studies have focused on macro-level SPF transferability. There has been little transferability analysis of macro-level SPFs in the international context, especially between western countries. This study therefore evaluates the transferability of SPFs for several states in the USA (Illinois, Florida and Colorado) and for Italy. The SPFs were developed using data from counties in the United States and *provincias* in Italy, and the results revealed multiple common significant variables between the two countries. Transferability indexes were then calculated between the SPFs. These showed that the Italy SPFs for total crashes and bicycle crashes were transferable to US data after calibration factors were applied, whereas the US SPFs for total and bicycle crashes, with the exception of the Colorado SPF, could not be transferred to the Italian data. On the other hand, none of the pedestrian SPFs developed was transferable to other countries. This paper provides insights into the applicability of macro-level SPFs between the USA and Italy, and shows a good

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potential for international SPF transferability. Nevertheless, further investigation is needed of SPF transferability between a wider range of countries.

Keywords: safety performance function (SPF); crash prediction model; negative binomial model; transferability; transferability index; international transferability; macro-level safety; macroscopic safety

1. Introduction

Traffic safety has long been a major public health concern. According to the National Highway Traffic Safety Administration [1], 34 439 people were killed in traffic crashes in the United States in 2016. Traffic fatalities had been decreasing from 1988 to 2011, but have shown an increasing trend since 2012. This demonstrates the need for greater effort to improve traffic safety and public health in the country. One of the first steps in this effort is to develop a function for the relationship between the number of crashes and contributing factors. Safety performance functions (SPFs), or crash-prediction models, have played an important role in identifying contributing factors to crashes, predicting crash counts, identifying hotspots and assessing countermeasures. SPFs have generally been developed for both the micro and the macro levels. Micro-level safety studies focus on safety on segments or at intersections, and suggest specific engineering countermeasures [2–5]. On the other hand, macro-level (or zonal level) studies provide a broader perspective by examining safety in particular zones and proposing planning-level or policy-based proactive countermeasures [4, 6–16]. Since a great deal of time and effort is needed to estimate an SPF, many researchers have investigated whether SPFs could be applied to data from other regions – a concept known as transferability. The transferability of SPFs has been investigated at both micro and macro levels.

Some studies have shown that SPFs can easily be transferred to other jurisdictions or areas [17–23]. On the other hand, others have pointed to the poor transferability of SPFs [17, 24, 25]. In a recent study by Farid *et al.* [17], the authors explored the transferability of SPFs for rural multilane highways between Florida, Ohio and California. The results showed an inconsistency in transferability across the different states. The SPFs for Florida and California were more transferable to other states compared with the SPFs for Ohio. The authors also found that transferability was improved when pooled data from multiple states were used to develop the SPF.

Wang *et al.* [24] adopted the empirical Bayes (EB) method, which requires an SPF, to develop crash modification factors. The authors analysed the effects of employing several SPFs for different states on the values of crash modification factors. The crash modification factor of signalization in Florida was 0.785 when the Florida SPF was used. In contrast, the crash modification factors were 1.06 and 1.07, respectively, when the SPFs from the Highway Safety Manual [2] and Ohio were applied. The results suggested that applying SPFs for other states without thorough examination was not advisable.

Farid *et al.* [23] proposed a method that applied Bayesian informative priors to improve the transferability of SPFs. An SPF for rural divided multilane highways with a vague prior (or non-informative prior) was developed for each state, and the distribution of the estimated parameters was used as an information prior for developing SPFs for other states. The results indicated that the SPFs with informative priors outperformed those with vague priors, demonstrating that applying informative priors could enhance transferability. Venkataraman *et al.* [25] examined the temporal transferability of SPFs for different severity levels in California. The overdispersion was allowed to change across segments as a function of roadway geometric features. Overall, 60 models were estimated for five severity levels for each of the following periods: 2005–2010, 2011–2012 and 2005–2012. The results showed that transferability was poor, which indicated the time instability of SPFs. Farid *et al.* [26] explored the transferability of SPFs for rural divided multilane highways in Florida, Ohio, Illinois, Minnesota, California, Washington and North Carolina. The authors found that particular SPFs for Ohio, Illinois, Minnesota and California were transferable to any of these four states. The authors suggested a new calibration method (local regression) that could provide greater predictability than that of the Highway Safety Manual or other methods used in previous studies.

A number of studies examined transferability in the international context. Torre *et al.* [18] studied the transferability of SPFs for freeways in the United States to Italian data. The results indicated acceptable applicability of the transferred models to the Italian data, especially that relating to fatal and injury crashes. Nevertheless, the authors found a propensity to underestimate locations with high crash frequency. The authors recommended several improvements to localization methods, including local calibrations. Kaaf and Abdel-Aty [19] investigated the transferability of SPFs for urban multilane divided highways from the Highway Safety Manual to Riyadh, Saudi Arabia. Although the study found that local SPFs provided the best performance, the Highway Safety Manual SPFs were also useful if local calibration factors for Riyadh were applied. Elvik [20] explored the international transferability of crash modification functions for horizontal curves. The author reviewed crash modification functions for ten countries, and concluded that functions developed in different countries had significant similarities, but varied with respect to crash rates on sharp horizontal curves.

Very few studies have investigated the transferability of macro-level SPFs. Hadayeghi *et al.* [21] explored the temporal transferability of macro-level SPFs. The authors applied multiple assessment measures to evaluate whether the relationship between crash frequency and the explanatory variables was consistent across different years in the city of Toronto. The authors adopted the Bayesian updating approach and the calibration factor. They concluded that although the SPFs developed were not very transferable, relative transferability measures showed that the transferred SPFs could provide practical information. Khondakar *et al.* [22] examined the temporal and spatial transferability of macro-level SPFs for the Greater Vancouver Regional District (1996) and the Central Okanagan Regional District (2003). The results indicated good macro-level SPF transferability. The authors recommended that SPFs be transferred instead of using a poorly developed SPF without sufficient data of acceptable quality.

Although many studies have been conducted to assess the transferability of SPFs at the micro level, no study has investigated the international transferability of macro-level models. One of the challenges of exploring transferability at the macro level is the difficulty of identifying comparable geographic units (such as traffic analysis zones or census units) between different countries, because the requirements and purposes of these geographic units are not necessarily the same. We have found that certain political units (such as the county in the United States) are equivalent to the *provincia* in Italy. It is assumed there are some cultural similarities (including similarities in travel and driving cultures) between different western countries (including between North American and European countries). Nevertheless, it is still questionable whether SPFs developed in one western country are transferable to another. In this study, therefore, we aim to evaluate the transferability of crash models for several states in the USA (namely Illinois, Florida and Colorado) based on counties and for Italy based on *provincias*.

The remainder of the paper is organized as follows. Modelling approaches, the calibration process and transferability indexes are explained in the methodology section. This is followed by the results and discussion section, which provides modelling results, transferability indexes and discussions of the results. The paper is summarized and concluded in the final section.

2. Methodology

Poisson or negative binomial models are commonly used for crash analysis because they offer the ability to relate the number of crashes to explanatory variables; however, Poisson models have been criticized because of their implicit assumption that the variance equals the mean. This assumption is often violated in crash data, in which the variance exceeds the mean of the crash frequency, which is termed overdispersion. In negative binomial models, this overdispersion is handled by the following mean–variance relationship [27]:

$$\text{Var}\ (Y) = \mu + \alpha\mu^2 \tag{1}$$

where Var (Y) is the variance of the crash frequency Y, μ is the mean of the crash frequency and α is the overdispersion.

Because negative binomial models are easy to estimate and account for overdispersion, they have been used most widely in the literature, including in the Highway Safety Manual [2]. In the negative binomial model, the relationship between the number of crashes and covariates is as follows:

$$\lambda_i = \exp\left(\beta_0 + \sum\nolimits_{k=1} \beta_k X_{ik} + \varepsilon_i\right) \tag{2}$$

where λ_i is the Poisson mean of the crash frequency (expected crash frequency), β_0 is an intercept, X_{ik} are explanatory variables, β_k are the corresponding coefficients to be estimated and $\exp(\varepsilon_i)$ is an error term following the gamma distribution with mean one and variance α [27, 28].

A calibration factor adjusts the total number of predicted crashes to the total number of observed crashes in the study area. The calibration factor is used to account for differences between the states in the USA and Italy for which the SPFs were developed and the study areas to which the SPFs are then applied. The calibration is calculated as follows:

$$C = \sum_{all\ sites} N_{obs_i} / \sum_{all\ sites} N_{prd_i} \tag{3}$$

where C is the calibration factor, N_{obs_i} is the observed number of crashes at county or *provincia* i and N_{prd_i} is the predicted number of crashes at i based on the developed SPF.

A transferability index (TI) is a measure of the transferability of SPFs [21, 29]. A TI compares the local intercept-only model with the transferred model. The equation to estimate a TI is as follows:

$$TI_j(\beta_i) = \left[LL_j(B_i) - LL_j(B_{reference,j})\right] / \left[LL_j(B_j) - LL_j(B_{reference,j})\right] \tag{4}$$

where$TI_j(\beta_i)$ is the transferability index of the SPF for state or *provincia* i, when it is applied to the data for state or *provincia* j, $LL_j(B_i)$ is the log-likelihood of the SPF developed from data i, as applied to j, $LL_j(B_j)$ is the log-likelihood of the SPF for j and $LL_j(B_{reference,j})$ is the log-likelihood of the intercept-only model of j.

Thus, if the TI is close to 1, the transferred SPFs developed from data for state or *provincia* i is more transferable to state or *provincia* j. On the other hand, if the TI is less than 1, the transferred SPF performs worse than the local intercept-only model.

3. Data collection

A county in the United States is a political subdivision of a state, which might include municipalities and unincorporated areas. An Italian *provincia* is a political subdivision of a *regione*. The *provincia* in this study include not only rural areas but also 10 metropolitan cities (for example, Rome, Milan and Turin). Before the data collection, we examined counties in the United States are comparable to *provincias* in Italy. Table 1 summarizes the average area, population and population density of a US county (organized by state) and an Italian *provincia*, while Fig. 1 presents these in the same scale. The average area of a *provincia* is about 5100 km², which is similar to that of an Illinois county (∼4200 km²) but greater than those of counties in Florida (∼2500 km²) and Colorado (∼1500 km²). Although Italy has the largest population of the areas in this study, Florida has a higher population density compared to Italy and other US states. It can be seen that Illinois, Florida and the US pooled data have comparable population density to that of Italy. There are some differences in size, population and population density, but these differences are not significant. We therefore concluded that the data sets from US states and Italy were comparable and could be analysed simultaneously.

Illinois crash data was collected from the Highway Safety Information System (HSIS). Crash data for Florida and Colorado was obtained from the Department of Transportation in each state. Demographic, socio-economic and transportation data was acquired from the US Census Bureau. Crash data (excluding pedestrian data) for Italy was collected from *Automobile Club d'Italia* (ACI), while pedestrian crash data was obtained from the *Istituto Nazionale di Statistica* (ISTAT). The crash data was provided by *provincia*. Demographic, socio-economic and transportation data for Italy was also acquired from ISTAT. The collected data for both the USA and Italy pertained to 2014.

Only data commonly available in the study areas was processed. In the United States, the data relating to major modes of transportation refers only to commute trips, while it refers to total trips in Italy. However, we assumed that commute trips can generally be used to represent total trips. The dependent variables are the numbers of road users involved in crashes, and candidate independent variables are population, population density, population proportions by age group, major modes of transportation, personal income (converted to US dollars, based on 2014) and occupation. The prepared data is summarized in Table 2.

4. Results and Discussion

The SPFs for the total number of crash-involved road users, bicyclists and pedestrians were developed using data for Italy, Illinois, Florida, Colorado and the US pooled data. Table 3 presents the modelling result. As expected, the natural logarithm of the population was significant and had a positive

Table 1. Comparison of area, population and population density of US counties and Italian *provincias*

Study area	Average area of county/*provincia* (km^2)	Population	Population density
Illinois (102 counties)	4216.203	12 868 747	85.810
Florida (67 counties)	2541.851	19 361 792	113.690
Colorado (64 counties)	1470.266	5 197 580	19.262
US pooled (233 counties)	2532.653	37 428 119	63.426
Italy (110 *provincias*)	5100.120	60 841 827	108.450

Fig. 1. US counties and Italian *provincias* in the study area in the same scale: (a) Illinois (n=102); (b) Florida (n=67); (c) Colorado (n=64); (d) Italy (n=110)

association with the dependent variable. The coefficient value was quite similar, ranging from 0.9589 to 1.1624. The proportion of people aged 5 to 14, which represents school-aged children, was significant in both Illinois and Florida and had a negative effect. The effect of the proportion of people aged 65 to 74 differed across the localities. In Illinois and Colorado, the variable had a positive coefficient, whereas it had a negative coefficient in Florida. The proportion of people whose major mode of transportation was walking had a positive association with the total number of crash-involved road users in the SPFs for Florida and the US pooled data. The proportion of people whose major mode of transportation was the motorcycle had a contrasting effect in the SPFs for the US pooled data and

Table 2. Descriptive statistics of the collected data (2014)

Variable	Illinois ($n = 102$)		Florida ($n = 67$)		Colorado ($n = 64$)		US pooled ($n = 233$)		Italy ($n = 110$)	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Dependent variables										
Total number of crash-involved drivers and other road users	2863.03	14 228.77	5555.16	12 751.95	1805.44	3810.06	3346.67	11 853.61	3022.86	4481.50
Number of crash-involved bicyclists	31.03	219.17	102.88	194.11	37.28	76.55	53.41	184.99	164.14	229.15
Number of crash-involved pedestrians	42.58	322.41	102.09	211.38	21.86	53.53	54.00	244.45	194.12	325.01
Demographic variables										
Population	1 26 164.19	5 30 701.61	2 88 981.97	4 62 594.05	81 212.19	1 63 625.80	1 60 635.70	4 44 724.55	5 53 108.73	5 98 355.84
Log of population	10.40	1.30	11.56	1.50	9.76	1.74	10.56	1.64	12.89	0.76
Population density	75.956	244.769	133.915	206.335	58.940	220.350	87.948	228.658	265.800	336.861
Proportion of people aged 5–14	0.126	0.015	0.113	0.018	0.120	0.028	0.121	0.021	0.091	0.010
Proportion of people aged 15–24	0.130	0.036	0.126	0.033	0.119	0.035	0.126	0.035	0.098	0.015
Proportion of people aged 65–74	0.091	0.016	0.108	0.040	0.096	0.038	0.097	0.032	0.107	0.011
Proportion of people aged 75 and older	0.080	0.016	0.084	0.034	0.065	0.030	0.077	0.027	0.109	0.017
Socioeconomic and transportation variables										
Proportion of people whose major mode of transportation is walking	0.025	0.015	0.016	0.011	0.062	0.054	0.033	0.035	0.226	0.081
Proportion of people whose major mode of transportation is the bicycle	0.003	0.005	0.006	0.010	0.014	0.026	0.007	0.015	0.027	0.036
Proportion of people whose major mode of transportation is the motorcycle	0.009	0.004	0.017	0.011	0.011	0.008	0.012	0.009	0.021	0.021
Proportion of people whose major mode of transportation is public transportation	0.011	0.021	0.012	0.019	0.019	0.032	0.013	0.024	0.312	0.069
Personal income (1000 USD)	14.226	2.225	13.119	3.282	15.635	4.436	14.295	3.385	19.020	4.546
Proportion of service occupations	0.714	0.057	0.775	0.069	0.760	0.067	0.744	0.069	0.658	0.062

Italy. In the US pooled SPF, it was negatively associated with the total number of crash-involved road users, whereas it had a positive association in Italy. Last, personal income was similarly significant in the SPFs for Colorado, the US pooled data and Italy, and had a positive effect. It is interesting that these coefficients were very close to each other.

Table 4 summarizes the transferability indexes for the SPFs for the total number of crash-involved road users. The transferability indexes before calibration show that the Illinois SPF could be applied to Colorado and the US pooled data. Similarly, the Colorado SPF was transferable to Illinois, Florida and the US pooled data. The US pooled SPF was applicable to all three US states. However, the Italy SPF could not be applied to the US states, nor were the US SPFs transferable to Italy. The transferability indexes after calibration show significant improvements in transferability. The Italy SPF was now applicable to all the US data, while the Colorado SPF could be transferred to the data for Italy.

Table 3. Safety performance functions for the total number of crash-involved road users

Variable	Illinois ($n = 102$)	Florida ($n = 67$)	Colorado ($n = 64$)	US pooled ($n = 233$)	Italy ($n = 110$)
Intercept	−4.3514 (****$P < 0.0001$)	−5.3619 (****$P < 0.0001$)	−4.6317 (****$P < 0.0001$)	−4.3794 (****$P < 0.0001$)	−7.3505 (****$P < 0.0001$)
Log (population)	1.0473 (****$P < 0.0001$)	1.1624 (****$P < 0.0001$)	0.9589 (****$P < 0.0001$)	0.9701 (****$P < 0.0001$)	1.0622 (****$P < 0.0001$)
Proportion of people aged 5–14	−3.3077 (*$P = 0.0204$)	−4.7067 (*$P = 0.0395$)	N/A	N/A	N/A
Proportion of people aged 65–74	3.9155 (*$P = 0.0196$)	−3.7857 (***$P = 0.0002$)	4.8057 (**$P = 0.0020$)	N/A	N/A
Proportion of people whose major mode of transportation is walking	N/A	5.9884 (*$P = 0.0282$)	N/A	3.4391 (****$P < 0.0001$)	N/A
Proportion of people whose major mode of transportation is the motorcycle	N/A	N/A	N/A	−8.0026 (**$P = 0.0033$)	9.8745 (****$P < 0.0001$)
Personal income (1000 USD)	N/A	N/A	0.0393 (****$P < 0.0001$)	0.0492 (****$P < 0.0001$)	0.0533 (****$P < 0.0001$)
Dispersion	0.0358	0.0481	0.1372	0.1080	0.2133
LL (null)	−879.242	−625.026	−519.789	−2033.23	−991.512
LL (full)	−639.4651	−479.3346	−410.5281	−1603.3542	−895.7526
Rho-squared	0.273	0.233	0.210	0.211	0.097
AIC	1288.9302	970.6691	831.0563	3218.7083	1801.5052
BIC	1302.0550	983.8973	841.8507	3239.4145	1815.0076

Table 4. Transferability indexes for SPFs for the total number of crash-involved road users

(a) Transferability indexes before calibration

SPF → Data ↓	Illinois	Florida	Colorado	US pooled	Italy
Illinois	1.000	−0.843	**0.856**[a]	**0.876**	−6.943
Florida	−1.076	1.000	**0.476**	**0.768**	−3.092
Colorado	**0.132**	−2.630	1.000	**0.904**	−10.569
US pooled	**0.248**	−0.778	**0.914**	1.000	−7.586
Italy	−29.192	−39.883	−6.276	−12.316	1.000

[a]TIs in bold are greater than zero.

(b) Transferability indexes after calibration

SPF → Data ↓	Illinois	Florida	Colorado	US pooled	Italy
Illinois	1.000	−0.815	**0.832**[a]	**0.903**	**0.724**
Florida	−0.076	1.000	**0.527**	**0.645**	**0.764**
Colorado	**0.314**	−1.261	1.000	**0.913**	**0.563**
US pooled	**0.306**	−0.571	**0.933**	1.000	**0.809**
Italy	−2.080	−7.652	**0.715**	−0.412	1.000

[a]TIs in bold are greater than zero.

Table 5 presents the SPFs for the number of crash-involved bicyclists. The exposure variable, the natural logarithm of the population, had a positive effect, and the coefficient values of the SPFs for the US states and Italy were comparable. The proportion of people aged 65 to 74 had a positive effect in Colorado, the US pooled data and Italy, whereas the proportion of people aged 75 and older had a negative effect in the US pooled SPF. The proportion of people whose major mode of transportation was the bicycle was significant and had a positive effect across all study areas. Personal income was also significant in all localities, though its effect in Illinois was negative, while it was positive in other areas.

Table 6 shows the transferability indexes for the SPFs for the number of crash-involved bicyclists. The table shows that before calibration, the Florida

Table 5. Safety performance functions for the number of crash-involved bicyclists

Variable	Illinois ($n = 102$)	Florida ($n = 67$)	Colorado ($n = 64$)	US pooled ($n = 233$)	Italy ($n = 110$)
Intercept	−11.9010 (****$P < 0.0001$)	−12.9195 (****$P < 0.0001$)	−9.1786 (****$P < 0.0001$)	−11.9199 (****$P < 0.0001$)	−13.4345 (****$P < 0.0001$)
Log (population)	1.3157 (****$P < 0.0001$)	1.3063 (****$P < 0.0001$)	0.9583 (****$P < 0.0001$)	1.1510 (****$P < 0.0001$)	1.0836 (****$P < 0.0001$)
Proportion of people aged 65–74	N/A	N/A	9.6916 (**$P = 0.0015$)	22.8935 (****$P < 0.0001$)	15.9638 (*$P = 0.0115$)
Proportion of people aged 75 and older	N/A	N/A	N/A	−21.5194 (****$P < 0.0001$)	N/A
Proportion of people whose major mode of transportation is the bicycle	19.8712 ($P = 0.0625$)	30.0285 (****$P < 0.0001$)	9.3280 (**$P = 0.0092$)	18.8021 (****$P < 0.0001$)	9.6914 (****$P < 0.0001$)
Personal income (1000 USD)	−0.0581 (*$P = 0.0457$)	0.0443 (**$P = 0.0094$)	0.0635 (**$P = 0.0045$)	0.0734 (****$P < 0.0001$)	0.1052 (****$P < 0.0001$)
Dispersion	0.0702	0.0576	0.2863	0.4285	0.2924
LL (null)	−336.744	−337.296	−266.944	−953.877	−668.659
LL (full)	−202.214	−234.180	−205.568	−730.216	−575.854
Rho-squared	0.400	0.306	0.230	0.234	0.139
AIC	414.4280	478.3593	423.1362	1474.4326	1163.7087
BIC	427.5529	489.3827	436.0895	1498.5899	1179.9116

SPF was transferable to Illinois and the US pooled data, the Colorado data was applicable to Florida and the US pooled data, the US pooled SPF could be transferred to all other areas and the Italy SPF was transferable to Illinois. Transferability was significantly improved after calibration. For instance, the Illinois SPF was now transferable to Florida, the Colorado SPF was applicable to all other areas and all US SPFs were now transferable to any other area.

Table 7 presents the safety performance functions for the number of crash-involved pedestrians. The natural logarithm of the population had a positive effect. As with the previous SPFs, the coefficients of the variable were very close across all areas. The proportion of people aged 65 to 74 was significant only in Italy. The proportion of people whose major mode of transportation was walking was significant and had a positive effect in all areas, while the proportion of people whose major mode of transportation was public transportation was significant only in Florida, where it was positively associated with the number of crash-involved pedestrians. It was found that personal income had a positive effect only in Italy.

Table 8 presents the transferability indexes for the models for the number of crash-involved pedestrians. The table indicates that transferability could not be significantly improved in this case even after calibration. Before calibration, the Illinois, Colorado and US pooled SPFs could be applied to other US states, whereas the Florida SPF could be transferred only to the US pooled data. The Italy SPF was transferable to Illinois, while none of the US SPFs was transferable to Italy. After calibration, the Italy SPF became non-transferable to Illinois, and no significant change could be observed.

5. Summary and conclusions

In this study, the transferability of SPFs for the United States and Italy was investigated. In contrast to micro-level studies, it is difficult to transfer SPFs to other countries at the macro level because of the need for comparable geographic units between the two countries under examination. We found that US counties and Italian *provincias* were reasonably comparable, in terms of average area and population density. It is worth investigating the transferability of SPFs between western countries because it is likely that these countries will share similar travel and driving cultures, and such similarities might affect transferability. To the authors' knowledge, this study is the first to explore the transferability of macro-level SPFs between countries.

Data for each of the study areas was collected and processed, and SPFs for the total numbers of crash-involved road users, bicyclists and pedestrians were developed. The modelling results showed multiple common significant variables in the SPFs. It was seen that the coefficient values of the exposure variable, the natural logarithm of the

Table 6. Transferability indexes for SPFs for the number of crash-involved bicyclists

(a) Transferability indexes before calibration

SPF → Data ↓	Illinois	Florida	Colorado	US pooled	Italy
Illinois	1.000	**0.592**[a]	−0.259	**0.769**	**0.688**
Florida	−0.017	1.000	**0.218**	**0.677**	−0.396
Colorado	−6.067	−2.328	1.000	**0.612**	−3.118
US pooled	−1.014	**0.236**	**0.276**	1.000	−0.567
Italy	−3.176	−8.808	−0.948	**0.626**	1.000

[a]TIs in bold are greater than zero.

(b) Transferability indexes after calibration

SPF → Data ↓	Illinois	Florida	Colorado	US pooled	Italy
Illinois	1.000	**0.870**[a]	**0.265**	**0.835**	**0.621**
Florida	**0.641**	1.000	**0.424**	**0.653**	**0.499**
Colorado	−1.296	−2.170	1.000	**0.726**	**0.876**
US pooled	−0.163	**0.011**	**0.555**	1.000	**0.732**
Italy	−3.660	−10.488	**0.884**	**0.471**	1.000

[a]TIs in bold are greater than zero.

Table 7. Safety performance functions for the number of crash-involved pedestrians

Variable	Illinois ($n = 102$)	Florida ($n = 67$)	Colorado ($n = 64$)	US pooled ($n = 233$)	Italy ($n = 110$)
Intercept	−13.0356 (****$P < 0.0001$)	−11.7812 (****$P < 0.0001$)	−14.0607 (****$P < 0.0001$)	−13.1925 (****$P < 0.0001$)	−14.3293 (****$P < 0.0001$)
Log (population)	1.3400 (****$P < 0.0001$)	1.2587 (****$P < 0.0001$)	1.4474 (****$P < 0.0001$)	1.3779 (****$P < 0.0001$)	1.1628 (****$P < 0.0001$)
Proportion of people aged 65–74	N/A	N/A	N/A	N/A	27.9499 (****$P < 0.0001$)
Proportion of people whose major mode of transportation is walking	7.1892 ($P = 0.0848$)	18.5947 (****$P < 0.0001$)	9.6092 (**$P = 0.0063$)	7.1696 (***$P = 0.0008$)	1.1639 (*$P = 0.0167$)
Proportion of people whose major mode of transportation is public transportation	N/A	4.1563 ($P = 0.0940$)	N/A	N/A	N/A
Personal income (1000 USD)	N/A	N/A	N/A	N/A	0.0449 (****$P < 0.0001$)
Dispersion	0.2020	0.0434	0.2204	0.1898	0.1194
LL (null)	−337.876	−346.738	−194.143	−894.687	−689.814
LL (full)	−223.470	−231.928	−126.928	−611.783	−565.195
Rho-squared	0.339	0.331	0.346	0.316	0.181
AIC	454.9390	473.8558	261.8569	1231.5648	1142.3896
BIC	465.4389	484.8792	270.4925	1245.3690	1158.5925

population, were similar in the SPFs for the same dependent variable. For the total number of crash-involved road users, three variables (the natural logarithm of the population, the proportion of people whose major mode of transportation is the motorcycle and personal income) were significant in the SPFs for both the US pooled data and Italy. However, the motorcycle variable had a contrary effect in each area. The motorcycle proportion was negatively associated with the number of crash-involved road users in the US pooled SPF, whereas it was positively associated in the Italy SPF. Both population and personal income had a positive relationship with the total number of crash-involved road users in the US pooled and Italy SPFs. The transferability indexes after calibration showed that the Italy SPF was transferrable to Illinois, Florida, Colorado and the US pooled data, whereas only the Colorado SPF was applicable to Italy for the total number of crash-involved road users.

Table 8. Transferability indexes for SPFs for the number of crash-involved pedestrians

(a) Transferability indexes before calibration

SPF → Data ↓	Illinois	Florida	Colorado	US pooled	Italy
Illinois	1.000	−0.233	**0.940**[a]	**0.935**	**0.062**
Florida	**0.586**	1.000	**0.784**	**0.813**	−1.910
Colorado	**0.911**	−0.300	1.000	**0.992**	−1.281
US pooled	**0.915**	**0.297**	**0.992**	1.000	−0.998
Italy	−1.325	−81.950	−3.813	−2.413	1.000

[a]TIs in bold are greater than zero.

(b) Transferability indexes after calibration

SPF → Data ↓	Illinois	Florida	Colorado	US pooled	Italy
Illinois	1.000	**0.521**[a]	**0.855**	**0.983**	−0.301
Florida	**0.854**	1.000	**0.725**	**0.823**	−3.553
Colorado	**0.985**	**0.376**	1.000	**0.988**	−0.121
US pooled	**1.020**	**0.360**	**0.905**	1.000	−0.866
Italy	−1.606	−64.638	−4.631	−1.989	1.000

[a]TIs in bold are greater than zero.

With respect to the SPFs for the number of crash-involved bicyclists, three variables were found to be similarly significant in the US pooled data and Italy: the natural logarithm of the population, the proportion of people aged 65 to 74 and the proportion of people whose major mode of transportation was the bicycle. These common variables were positively associated with the number of crash-involved bicyclists. The transferability indexes after calibration indicated that the Italy SPF could be transferred to Illinois, Florida, Colorado and the US pooled data, while the Colorado and US pooled SPFs could be applied to Italy.

Regarding the SPFs for the number of crash-involved pedestrians, only two variables were similarly significant in the SPFs for both the US pooled data and Italy: the natural logarithm of the population and the proportion of people whose major mode of transportation was walking. Both variables were positively associated with the number of crash-involved pedestrians. The transferability indexes after calibration showed that the Italy SPF was not transferable to any of the US areas and the US SPFs were not applicable to Italy, which was quite different from the bicyclist data. It is possible that the reason for the non-transferability of the pedestrian SPFs lies in the difference in travel behaviour between the two countries. In the USA and Italy, bicycles are not considered a major mode of transportation (USA: 7%; Italy: 2.7%). On the other hand, walking is one of the major modes of transportation in Italy (22.6%) while it is not in the USA (3.3%).

The major contribution of this paper is to evaluate the transferability of macro-level SPFs in the international context. There have been several studies exploring the transferability of macro-level SPFs and investigating the transferability of micro-level SPFs between countries. The finding that calibration can significantly improve the transferability of SPFs is also important. Nevertheless, no study has examined the international transferability of macro-level SPFs. This paper provides insights into the applicability of macro-level SPFs between the USA and Italy, and shows a great potential for international transferability. Nevertheless, this study is not without limitations. For example, there are relatively few common candidate variables between countries. Additionally, traffic safety was analysed only at county and *provincia* level. It is possible that different results would be found if smaller or larger geographic units were used. Further research is also needed to explore the transferability of SPFs between a greater number of countries in order to reach more general conclusions. These limitations should be addressed in follow-up studies.

6. Author contribution statement

The authors confirm that their contributions to this paper were as follows: Jaeyoung Lee, Mohamed Abdel-Aty, Maria Rosaria de Blasiis and Xuesong Wang conceived and designed the study; Jaeyoung Lee, Maria Rosaria de Blasiis and Ilaria Mattei collected the data; Jaeyoung Lee, Mohamed Abdel-Aty, Maria Rosaria de Blasiis and Ilaria Mattei analysed and interpreted the results; and Jaeyoung Lee, Mohamed Abdel-Aty, Xuesong Wang and Maria Rosaria de Blasiis drafted the manuscript. All authors reviewed the results and approved the final version of the manuscript.

Conflict of interest statement. None declared.

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