Advancing Innovating Intersection Safety Treatments for Two-Lane Rural Highways

Executive Summary

FHWA Safety Program

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16. Abstract

Intersection safety is a national, state, and local priority. Approximately 26 percent of the fatal crashes that occur in the United States are intersection or intersection-related crashes. The objective of this guide is to advance efforts to improve safety at unsignalized intersections with minor-road stop control along rural two-lane roads, by focusing on strategies that are not yet widespread. The safety effectiveness of three low-cost safety treatments was evaluated to estimate their expected effectiveness in reducing crashes. The low-cost safety treatments included: (1) single luminaire intersection lighting, (2) transverse rumble strips in advance of stop-controlled approaches, and (3) supplementary pavement markings on intersection approaches.

The effectiveness of each treatment in reducing crashes was estimated using the Empirical Bayes (EB) observational before-after safety evaluation analysis approach. Analyses were performed to estimate the effectiveness of each treatment in reducing crashes for different severity levels and crash types. An economic analysis of the treatments was also performed. Each of the treatments is effective in reducing crashes of different types and severity levels, and is economically justifiable for most traffic volumes.

The information in this report can be combined with information on other strategies to reduce intersection or intersection-related crashes at unsignalized intersections with minor-road stop control along rural two-lane roads. With such information, agencies can make informed decisions about planning and programming safety improvements at intersections under their jurisdiction.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

EXECUTIVE SUMMARY

BACKGROUND

Intersection safety is a national, state, and local priority. Approximately 26 percent of fatal crashes in the United States occur at intersections.[1,2] In the period between 2009 and 2013, the average number of intersection-related fatalities was approximately 7,960 per year .[2]

Crashes in rural areas are often more severe than in urban areas because of higher vehicle speeds, and the outcome of crashes may be more severe, in part, due to longer emergency response times. In rural areas, more fatal and severe-injury crashes occur at stop-controlled intersections than at signalized intersections.[3] At stop-controlled intersections, most crashes are caused by a failure to stop at a stop-controlled approach or the acceptance of an insufficient gap when entering the intersection.[4]

The objective of this study was to increase the deployment of low-cost treatments that reduce motor vehicle fatalities and injuries at intersections with minor-road stop control along rural two-lane roads. Information in this report can be combined with information about other strategies available in references such as the *Highway Safety Manual* (HSM)[5] and the Federal Highway Administration's (FHWA's) Crash Modification Factors (CMFs) Clearinghouse[6] to reduce intersection or intersection-related crashes at rural unsignalized intersections. With such information, agencies can make informed decisions about planning and programming safety improvements at intersections under their jurisdiction. FHWA sponsored research to evaluate treatments for rural stop-controlled intersections that were in use by highway agencies but for which little quantitative information about their safety effectiveness was available. A wide range of treatments was initially considered for the research. The list was reduced to three treatments based on availability of study sites, crash data, traffic volumes, and other data, as well as on priorities of FHWA. The three treatments for which detailed analyses were conducted included single luminaire lighting, transverse rumble strips, and supplementary pavement markings.

ANALYSIS APPROACH

The safety effectiveness of each treatment was estimated by conducting an Empirical Bayes (EB) before-after crash analysis. The EB before-after crash analyses were conducted in accordance with steps outlined in Appendix 9A of the HSM[5] to estimate the expected reduction in crash frequency due to implementation of the treatment. In all cases, safety performance functions (SPFs) presented in the HSM for stop-controlled intersections on rural two-lane roads were used. The intersection SPFs predict crashes based on the annual average daily traffic (AADT) of the major and minor roads and are adjusted using CMFs for intersection skew angle (CMF_{Skew}), number of major-road left-turn lanes (CMF_{LTL}), number of major-road right-turn lanes (CMF_{RTL}), and the presence of intersection lighting ($CMF_{Lighting}$). (For the safety evaluation of single luminaires, $CMF_{Lighting}$ was not included in the predictions.) Target crash type proportions (PR_1) and severity proportions (PR_2), which were either taken from default proportions presented in the HSM or calculated from crash data obtained for each state, were used to predict the number of total crashes by crash type and crash severity categories. Calibration factors (C_r) were calculated for each state to account for state-to-state differences in crash experience. The general form of the SPFs, including CMFs for intersections on rural two-lane roads, crash type and severity proportions, and calibration for local conditions, is as follows (see Figure 1):

$$\text{Predicted crashes/yr} = \{\exp[a + b(\ln AADT_{maj}) + c(\ln AADT_{min})]\} \times CMF_{Skew} \times CMF_{LTL} \times CMF_{RTL} \times CMF_{Lighting} \times PR_1 \times PR_2 \times C_r$$

Figure 1. Equation. Model for predicted crashes per year for specific crash types and severity levels, and accounting for local conditions.

where regression coefficients a, b, and c, CMF values, and default values for PR_1 and PR_2, if used, are provided in Chapter 10 of the HSM.

Using the results from the EB before-after crash analyses, economic analyses were then performed to estimate the benefit-cost ratios of each treatment. This ratio is the annual economic benefit divided by the annualized treatment cost. Benefit-cost ratios greater than one can be used to justify installation of a specific treatment. Crash reduction benefits were calculated using the HSM predictive methodology to estimate the number and severity of crashes that would be expected without the installation of the treatment and then applying the CMFs developed in this research to determine the expected annual change in crash frequency and severity. The economic values associated with crashes at each severity level were those presented in Chapter 7 of the HSM. A range of AADT values for the major and minor roads, representing the range of AADTs observed at the sites included in the analysis, was used to generate a matrix of possible crash reduction scenarios. Crash costs (by severity level) from the HSM were applied to the change in crashes expected due to the treatment to determine the economic benefit of the treatment. The treatment installation, maintenance costs, and service life cycles used in the analyses were gathered from state DOTs. In some cases, upper and lower ranges of treatment costs and/or service life cycles were used to determine the range of benefit-cost ratios that might be expected for a treatment.

TREATMENT: SINGLE LUMINAIRE LIGHTING

Single luminaires are used to reduce nighttime crashes by making drivers aware of the presence of an intersection that may otherwise be difficult to see at night. The luminaire may be pole-mounted near one corner of the intersection or wire-mounted over the intersection (see Figure 2).

For drivers on a stop-controlled approach, increasing the visibility of the intersection may provide additional time to perceive the need to stop. For drivers on the uncontrolled approach, lighting may increase the visibility of vehicles, pedestrians, and bicyclists entering the roadway at that location and thus provide additional time to react appropriately.

Figure 2. Photo. Examples of single luminaire intersection lighting (Image Credit: Google Earth™ Mapping Service).[7]

Safety Analysis

The EB before-after crash analysis was based on data from 27 treatment and 61 nontreatment intersections in Minnesota. Data for both 3- and 4-leg intersections were combined in the analysis to maximize the available sample size. Basic intersection descriptives and crash summaries are provided in Table 1.

Table 1. Single luminaire study locations - summary statistics.

Intersection Characteristics	3- and 4-Leg Intersections		
	Treatment		
	Before	After	Nontreatment
Number of sites	27	27	61
Number of years	5	1 to 3	8 to 9
Number of site-years	135	43	509
$AADT_{maj}$ range (veh/day)	200 to 7,300	220 to 5,900	145 to 3,900
$AADT_{min}$ range (veh/day)	30 to 2,000	30 to 2,000	65 to 2,150
Number of total nighttime crashes	20	1	27
Number of FI nighttime crashes	7	1	9
Number of PDO nighttime crashes	13	0	18

The EB before-after crash analysis was performed for nighttime crashes at three severity levels: total, fatal and injury (FI), and property damage only (PDO).

The EB analysis results indicated that installing a single luminaire reduced total nighttime crashes by 71 percent (standard error of 0.29 percent); this safety effect was statistically significant at the 95-percent confidence level. An estimate could not be calculated for FI and PDO nighttime crashes due to the small number of target crashes in the dataset.

Economic Analysis

Benefit-cost ratios ranged from 0.5 to 35.0, assuming an $8,000 installation cost and $300 annual energy cost over a 20-year life, and using the CMF for total nighttime crashes (0.29) calculated by this research. The benefit-cost ratio exceeded 1.0 for intersections at which the major road carried at least 300 veh/day and the minor road carried at least 150 veh/day, and for all intersections at which the major-road AADT was at least 1,000 veh/day, regardless of the minor-road volume.

Implementation Considerations

Single luminaires should be considered at intersections with a high proportion of crashes occurring during hours of darkness, or simply at intersections with a moderate to high frequency of nighttime crashes. Intersections with patterns of nighttime crashes that suggest drivers are unaware of the presence of the intersection (such as near horizontal or vertical curves or in the case of significant intersection skew) may especially benefit from this treatment.

If there is vegetation near the intersection, foliage should be trimmed and maintained on a regular basis so it does not cause shadows or reduce the visibility generated from the luminaire. Luminaire poles should have a breakaway design and should be located to minimize the risk of being struck by a vehicle.

Annual energy costs can be substantially reduced if solid-state LED luminaires are used, and solar-powered luminaires eliminate the need for a wired power source near the intersection.

TREATMENT: TRANSVERSE RUMBLE STRIPS

Transverse rumble strips are placed in the travel lane perpendicular to the direction of travel. When used on the approach to a stop-controlled intersection, they are often applied in two or more sets of individual closely-spaced strips, and often used to supplement stop-ahead warning signs. They are designed to generate noise and vibration in the vehicle as the vehicle passes over them to alert the driver to the stop condition ahead. Transverse rumble strips may be rolled or grooved into asphalt, formed into fresh concrete, or created as epoxy strips on the surface of the pavement. Figure 3 shows an example of rumble strips milled into asphalt.

Figure 3. Photo. Example of transverse rumble strips placement (Image Credit: Google Earth™ Mapping Service).(7)

Safety Analysis

The EB analysis was based on before and after traffic volumes and crash data from 72 treatment and 126 nontreatment sites in five states—Arkansas, Kansas, Missouri, North Dakota, and Oregon—separately for 3- and 4-leg intersections. Basic intersection descriptives and crash summaries are provided in Table 2.

Three crash types were analyzed: all collision types combined, angle crashes, and rear-end crashes, and each crash type was broken down by severity level. Analysis results are shown in Table 3, for crash types and severity levels with statistically significant reductions in crashes at the 90 percent confidence level or higher.

Economic Analysis

Assuming a $5,000 installation cost per approach and a 20-year life cycle, benefit-cost ratios ranged from 1.1, for a major-road AADT of 200 veh/day and a minor-road AADT of 90 veh/day, to more than 50 when the major-road AADT exceeded 5,000 veh/day. When a $1,000 installation cost per approach and a 5-yr service life were assumed, benefit-cost ratios over the same range of AADTs ranged from 4.1 to more than 200. These results show transverse rumble strips to be highly cost effective at reducing crashes at rural two-lane intersections, even at very low volumes.

Table 2. Transverse rumble strips study locations - summary statistics.

Transverse Rumble Strips (Arkansas, Kansas, Missouri, North Dakota[1], and Oregon)	3-Leg Intersections			4-Leg Intersections		
	Treatment		Non-treatment	Treatment		Non-treatment
	Before	After		Before	After	
Number of sites	25	25	27	47	47	99
Number of years	4 to 5	2 to 9	9 to 14	3 to 5	1 to 10	8 to 16
Number of site-years	123	92	313	227	212	1,245
$AADT_{maj}$ range (veh/day)	245 to 8,900	255 to 11,700	245 to 8,900	165 to 6,700	198 to 6,700	65 to 15,900
$AADT_{min}$ range (veh/day)	110 to 6,000	120 to 7,000	110 to 6,000	65 to 4,118	85 to 3,547	65 to 4,118
Number of total crashes	30	31	133	121	227	624
Number of FI crashes	12	11	6	68	105	353
Number of PDO crashes	18	20	70	53	122	271
Number of angle crashes	3	5	9	73	135	333
Number of rear-end crashes	4	9	25	16	30	78

[1] No control intersections were available in North Dakota; nontreatment sites from Nebraska were used in the analysis.

Table 3. Safety effectiveness of transverse rumble strips on target crashes.

Crash Type	Severity Level	Number of Legs	Safety Effectiveness (%)	SE of Treatment Effect (%)	Statistically Significant at:
All	FI	3	-37	20	90% CL
Angle	PDO		-61	28	95% CL
Rear-end	FI		-60	29	95% CL
All	Total	4	-13	7	90% CL
	FI		-29	8	95% CL
Angle	FI		-25	10	95% CL
Rear-end	Total		-56	8	95% CL
	FI		-78	8	95% CL
	PDO		-54	10	95% CL

Implementation Considerations

Transverse rumble strips should be considered for stop-controlled approaches to intersections where crash patterns indicate that drivers fail to recognize the stop condition (e.g., angle crashes related to stop sign violations). Rumble strips may be especially effective on the stop-controlled approach to an intersection that is hidden from view due to horizontal or vertical curvature or that follows a long tangent section. The proximity of the intersection to nearby residences or businesses should be considered, as the treatment generates noise that residents may not appreciate. Typically, transverse rumble strips are considered for implementation after less intrusive measures have been tried and failed to improve the crash experience at an intersection.

Transverse rumble strips may have undesirable effects that should be considered prior to implementation including: potential loss-of-control problems for motorcyclists and bicyclists;

difficulties associated with snowplow operations; and inappropriate driver responses such as using the opposing travel lanes to drive around the rumble strips .[8]

TREATMENT: SUPPLEMENTARY PAVEMENT MARKINGS

This study considered two distinct types of supplementary pavement markings: markings on stop-controlled approaches (STOP AHEAD pavement markings) and markings on uncontrolled approaches (supplementary speed limit message [e.g., “SLOW, XX MPH,”] used with intersection ahead symbol [┼, ├, or ┤]), shown in Figure 4. In the first case, the pavement markings are used to alert drivers of the upcoming stop condition, while in the second case, the markings are used to alert drivers of the presence of the intersection and of the potential for vehicles and other road users entering or exiting the roadway at that location.

Figure 4. Photo. Aerial view and street view of supplementary pavement markings on stop-controlled approach (Image Credit: Google Earth™ Mapping Service)[7] and supplementary pavement markings on uncontrolled approach (Image Credit: Pennsylvania DOT)

Safety Analysis

The safety effectiveness of supplementary pavement markings was evaluated separately for markings installed on stop-controlled approaches of intersections and those installed on uncontrolled approaches since the two types of installations are very different in their mechanism for potentially reducing crashes.

Supplementary Pavement Markings Installed on Stop-Controlled Approaches:

The EB analysis was based on before and after traffic volumes and crash data from 76 treatment and 140 nontreatment sites in four states—Arkansas, Minnesota, Nebraska, and Vermont — separately for 3- and 4-leg intersections. Descriptive statistics of study sites are shown in Table 4.

Three crash types were analyzed: all collision types combined, angle crashes, and rear-end crashes, and each crash type was broken down by severity level. Data for 3- and 4-leg intersections were analyzed separately. Analysis results are shown in Table 5, for crash types and severity levels with statistically significant reductions in crashes at the 95 percent confidence level or higher.

Supplementary Pavement Markings Installed on Uncontrolled Approaches:

The EB analysis was based on before and after traffic volumes and crash data from 11 treatment and 28 nontreatment sites in Pennsylvania. Descriptive statistics of study sites are shown in Table 6.

Three crash types were considered in this analysis: all collision types combined, angle crashes, and rear-end crashes. Data for both 3- and 4-leg intersections were combined for analysis. Results are shown in Table 7, for crash types and severity levels with statistically significant reductions in crashes at the 95 percent confidence level or higher.

Table 4. Study locations with supplementary pavement markings installed on stop-controlled approach - summary statistics.

Supplementary Pavement Markings Installed on Stop-Controlled Approaches (Arkansas, Minnesota, Nebraska, and Vermont)	3-Leg Intersections			4-Leg Intersections		
	Treatment		Non-treatment	Treatment		Non-treatment
	Before	After		Before	After	
Number of sites	35	35	54	41	41	86
Number of years	3 to 5	1 to 16	8 to 20	3 to 5	2 to 16	13 to 20
Number of site-years	169	321	812	192	398	1,393
$AADT_{maj}$ range (veh/day)	90 to 4,700	102 to 5,700	90 to 8,900	105 to 3,900	134 to 4,800	105 to 6,600
$AADT_{min}$ range (veh/day)	40 to 2,395	40 to 3,000	40 to 5,800	25 to 1,766	25 to 1,500	25 to 2,510
Number of total crashes	25	32	293	49	100	497
Number of FI crashes	11	15	128	28	57	23
Number of PDO crashes	13	17	162	18	43	227
Number of angle crashes	3	3	47	23	46	257
Number of rear-end crashes	1	2	50	7	12	63

Table 5. Safety effectiveness of supplementary pavement markings installed on stop-controlled approaches on target crashes.

Crash Type	Crash Severity	Number of Legs	Safety Effectiveness (%)	SE of Treatment Effect (%)	Statistically Significant at:
All	Total	3	-67	7	95% CL
	FI		-76	7	95% CL
	PDO		-72	7	95% CL
Angle	Total	3	-92	5	95% CL
	FI		-88	7	95% CL
Rear-end	Total	3	-95	4	95% CL
	FI		-96	5	95% CL
	PDO		-97	3	95% CL
All	Total	4	-66	4	95% CL
	FI		-69	5	95% CL
	PDO		-77	4	95% CL
Angle	Total	4	-74	4	95% CL
	FI		-71	5	95% CL
	PDO		-88	3	95% CL
Rear-end	Total	4	-89	3	95% CL
	FI		-86	5	95% CL
	PDO		-95	2	95% CL

Table 6. Study locations with supplementary pavement markings installed on uncontrolled approaches - summary statistics.

Supplementary Pavement Markings Installed on Uncontrolled Approaches (Pennsylvania)	3- and 4-Leg Intersections		
	Treatment		Non-treatment
	Before	After	
Number of sites	11	11	28
Number of years	4 to 5	2 to 12	8 to 17
Number of site-years	52	58	404
$AADT_{maj}$ range (veh/day)	1,889 to 14,188	1,917 to 16,267	629 to 15,258
$AADT_{min}$ range (veh/day)	184 to 5,377	183 to 4,242	173 to 5,377
Number of total crashes	108	162	460
Number of FI crashes	61	79	269
Number of PDO crashes	47	83	191
Number of angle crashes	69	125	275
Number of rear-end crashes	14	20	58

Table 7. Safety effectiveness of supplementary pavement markings installed on uncontrolled approaches on target crashes.

Crash Type	Crash Severity	Safety Effectiveness (%)	SE of Treatment Effect (%)	Statistically Significant at:
All	Total	-46	5	95% CL
	FI	-49	7	95% CL
	PDO	-50	6	95% CL
Angle	Total	-38	7	95% CL
	FI	-42	8	95% CL
	PDO	-35	10	95% CL
Rear-end	Total	-69	7	95% CL
	FI	-76	9	95% CL
	PDO	-75	8	95% CL

Economic Analysis

For STOP AHEAD pavement markings, two scenarios were used in the benefit-cost analysis. When a $750 installation cost per approach and a 1-year service life were assumed, benefit-cost ratios at 3-leg intersections ranged from 1.8, for a major-road AADT of 200 veh/day and a minor-road AADT of 40 veh/day, to more than 170 at major-road AADTs above 5,000 veh/day. When a $500 installation cost per approach and a 2-year service life were assumed over the same ranges of AADTs, benefit-cost ratios ranged from 5.2 to more than 500 at the highest AADTs considered.

For the supplementary pavement markings used on uncontrolled approaches in Pennsylvania, a $10,000 installation cost and a 5-year service life were assumed. Benefit-cost ratios for this treatment ranged from 15.1, for a major-road AADT of 2,400 veh/day and a minor-road AADT of 360 veh/day, to more than nearly 140 for major-road AADTs above 13,000 veh/day and minor-road AADTs above 2,600 veh/day.

These results show both types of supplemental pavement markings are highly cost effective at reducing total crashes at rural two-lane intersections. While STOP AHEAD pavement markings were found to be effective even at intersections of very low volume roads, the pavement markings used on uncontrolled approaches were only found, and therefore evaluated, at intersections with higher volumes.

Implementation Considerations

Supplemental pavement markings should be considered at intersections with a crash pattern related to a lack of driver awareness of the presence of the intersection. However, supplementary pavement markings may not be visible during winter conditions with snow and ice, and they may have a lower coefficient of friction compared to the rest of the intersection approach, especially during wet conditions (7).

SUMMARY

The objective of this study was to increase the deployment of low-cost treatments that reduce motor vehicle fatalities and injuries at intersections with minor-road stop control along rural two-lane roads. The safety effectiveness of three low-cost safety treatments was evaluated using the EB observational before-after safety evaluation analysis approach to estimate their expected effectiveness in reducing crashes:

- Single luminaire intersection lighting
- Transverse rumble strips in advance of stop-controlled approaches
- Supplementary pavement markings on intersection approaches

In addition, economic analyses were performed to estimate the benefit-cost ratio of each treatment, incorporating safety effectiveness results from the EB analyses. The safety and economic analyses show that the treatments are effective in reducing crashes of different types and severity levels and are economically justifiable for installation at intersections with patterns of crashes that suggest drivers are unaware of the presence of the intersection. The results of this research can be combined with information on other strategies to reduce crashes at intersections with minor-road stop control along rural two-lane roads. With this information, agencies can make informed decisions to plan and program safety improvements at intersections under their jurisdiction.

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For More Information:

Visit http://fhwa.safety.dot.gov/intersection/

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