Safety Effects of Height of Central Islands, Sight Distances, Markings and Signage at Single-lane Roundabouts

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ABSTRACT
The height of central islands, sight distances, pavement markings and signage seem to have some influence on safety at single-lane roundabouts. The paper presents new information based upon a before-after safety study of converting intersections to 265 single-lane roundabouts in Denmark. Results from previous studies on these topics are included in the paper for comparison and discussion.

Non-transparent central islands higher than 1.9 meters produce better safety effects compared to lower central islands at single-lane roundabouts. A consequence of high central islands is fewer accidents between entering and circulating vehicles.

Certain approach sight distances may worsen safety at urban single-lane roundabouts. If upstream and circulating approach sight is given to approaching road users about 17-40 meters before the yield line then safety is not good.

If there is a truck apron around the central island then marking an edge line between the truck apron and the circulation seems to improve safety particularly at urban single-lane roundabouts. A two meters wide truck apron seems to be safest. Yield ahead signs and markings, roundabout plagues, destination signs and rumble strips all prior to the entry of single-lane roundabouts seem to improve safety considerably.

INTRODUCTION

Roundabouts as a type of intersection have become more and more popular in the past 2-4 decades. An example is that the number of roundabouts in Denmark has increased from about 50 in 1980 to 425 in 1995 and 1,450 in 2010. Roundabouts are often established due to road safety concerns, but often roundabouts also work well in terms of traffic operations.

The safety effects of converting intersections to roundabouts have been studied many times. Jensen (*1*) made a meta-analysis of larger before-after safety studies (*2-20*) of these conversions, see table 1. The meta-analysis methodology has been described by Elvik (*21*).

TABLE 1 Results from Meta-Analyses of Before-After Safety Studies of Conversions of Intersections to Roundabouts. A Total of 25,324 Accidents, 134 Fatalities and 3,500 Non-Fatal Injuries occurred at Converted Sites in the Studies

Conversions	Type of accident / injury	Included studies	Best estimate of safety effect	95 % confidence interval
All	Fatal accidents	*7, 15, 19, 20*	-77 %	-88 % ; -57 %
	Injury accidents	*2-5, 7-20*	-59 %	-65 % ; -52 %
	PDO accidents	*2-4, 7-8, 13-15, 18-20*	-25 %	-35 % ; -14 %
	All accidents	*2-20*	-43 %	-48 % ; -37 %
	Fatalities	*3, 4, 6, 7, 19, 20*	-83 %	-91 % ; -68 %
	Severe injuries	*3, 6, 7, 11, 19, 20*	-71 %	-80 % ; -60 %
	Slight injuries	*3, 6, 7, 19, 20*	-69 %	-77 % ; -59 %
	All injuries	*2, 3, 4, 6, 7, 19, 20*	-70 %	-77 % ; -62 %
In urban areas	All accidents	*3, 4, 6, 7, 9, 11, 13, 14, 18-20*	-24 %	-39 % ; -5 %
	All injuries	*3, 4, 6, 7, 19, 20*	-61 %	-76 % ; -39 %
In rural areas	All accidents	*3, 4, 6-9, 13, 14, 18-20*	-54 %	-60 % ; -47 %
	All injuries	*3, 4, 6, 7, 19, 20*	-83 %	-86 % ; -79 %
Of non-signalized intersections	All accidents	*2, 4, 7, 8, 10, 12, 13, 19*	-44 %	-50 % ; -37 %
	All injuries	*4, 7, 19*	-70 %	-78 % ; -61 %
Of signalized intersections	All accidents	*2, 7, 8, 10, 12, 14, 19*	-30 %	-38 % ; -20 %
	All injuries	*7, 19*	-48 %	-60 % ; -32 %
To 3-armed roundabouts	All accidents	*7, 12, 14, 19*	-24 %	-48 % ;+10 %
	All injuries	*7, 19*	-37 %	-52 % ; -18 %
To 4-armed roundabouts	All accidents	*4, 7, 12, 14, 19*	-41 %	-52 % ; -27 %
	All injuries	*4, 7, 19*	-72 %	-78 % ; -64 %
To 5-7-armed roundabouts	All accidents	*7, 19*	-26 %	-51 % ;+12 %
	All injuries	*7, 19*	-3 %	-49 % ;+88 %
To single-lane roundabouts	All accidents	*4, 8, 13, 14, 19*	-45 %	-57 % ; -30 %
To multi-lane roundabouts	All accidents	*8, 13, 14, 19*	-26 %	-41 % ; -8 %

Table 1 is based on meta-analyses without weights for study quality, whereas Jensen (*1*) showed weighted results. Weighted and unweighted results are similar e.g. an unweighted accident reduction of 43 % and a weighted reduction of 42 %.

Table 1 shows that converting intersections to roundabouts reduce the number of accidents and reduce injury severity. The safety effects of conversions are 22-30 percentage points better in rural areas compared to urban areas. Studies (*22, 23, 24*) show relations between safety effects of conversions and speed limits on approach roads. As speed limits increase safety effects become better. The safety effects of conversions of non-signalized intersections to roundabouts are 14-22 percentage points better compared to effects of conversions of signalized intersections. Safety effects of converting intersections to 4-armed roundabouts are better than converting to roundabouts with 3 or 5-7 arms. Conversions of intersections to single-lane roundabouts result in better safety effects compared to multi-lane roundabouts according to table 1. Studies (*1, 8*) show that safety effects of conversions to multi-lane turboroundabouts are similar to effects of conversions to single-lane roundabouts.

The long-term safety effects of converting intersections to roundabouts are better than short-term effects. Studies (*19, 25, 26*) show that safety effects in the first and second year after conversions are 7-13 percentage points worse compared to the effects 3-6 years after conversions. Jensen (*1*) finds that better long-term safety effects stem from better effects over time for single-vehicle accidents at roundabouts with central islands less than 1.5 meters high.

This paper focuses on parts of the roundabout design that only have been studied a few times before and on a rather limited scale. Design elements in focus are the height of the central islands, sight distances, pavement markings and signage at single-lane roundabouts. Previous research on these design elements are presented followed by new research. The new research is based on a before-after safety study of converting intersections to 265 single-lane roundabouts in Denmark. Before looking at these non-geometric roundabout design elements a literature review of relations between roundabout geometry and safety is given.

LITERATURE REVIEW OF ROUNDABOUT GEOMETRY AND SAFETY

Relations between safety and roundabout design have been studied numerous times. There seems to be three ways to do such studies. 1) Accident models that relate accident figures to traffic volumes and roundabout design are useful to describe relations, but accident models do not provide causal relationships. 2) Before-after safety studies of roundabout redesigns are rare, because roundabouts are seldom changed. 3) Before-after safety studies of converting intersections to roundabouts may be used, but it is difficult to deduce the safety impacts of roundabout design, because intersection design and site characteristics such as speed limits also influence safety effects of conversions.

Studies seem to indicate that central island diameters of about 20-40 meters including truck aprons provide the best level of safety at single-lane roundabouts. Lalani (*11*) shows that converting intersections to roundabouts in Greater London gave an accident reduction of 30 % with 1-4 meters central island diameters, 43 % with 4.1-7.9 meters diameters and 52 % with diameters of 8.0 meters or more. Brüde and Larsson (*27*) find that entry, circulating and exit speeds at 536 roundabouts were lowest at roundabouts with central island diameters of 20-40 meters. Jørgensen (*2*) finds a decreasing injury accident rate with increasing central island diameter and a high frequency of property-damage-only (PDO) accidents with 11-20 meters central island diameters. Montonen (*5*) shows that accident rates are lowest with central island diameters of 13-20 meters and highest with diameters of more than 30 meters, whereas injury accident rates are lowest with diameters of 21-30 meters. Jørgensen and Jørgensen (*4*) find that roundabouts in urban areas with central island diameters of about 15 meters are safer than roundabouts with smaller or larger central islands. Jørgensen and Jørgensen (*28*) find that roundabouts in rural areas with central island diameters of 20-40 meters have a lower accident rate than roundabouts with larger central islands. Brüde and Larsson (*29*) show that motor vehicle accident rate is lowest for roundabouts with central island diameters of 20-50 meters. Rodegerdts et al. (13) find weak relations showing that as the central island diameter increases the number of accidents between entering and circulating vehicles decreases and at the same time the number of accidents between exiting and circulating vehicles increases. Jensen (*1*) finds that conversions of intersections to single-lane roundabouts with central island diameters of 20-40 meters result in the best safety effects in urban and rural areas.

Studies indicate that safety improves as deflection increases until it reaches a given level and perhaps safety worsens if deflection becomes too large. Maycock and Hall (*30*) show that as deflection increases the number of accidents between entering and circulating vehicles decreases, whereas the number of single-vehicle accidents and accidents between approaching vehicles increases resulting in a U-shaped relationship between deflection and accident rate. Spacek (*31*) finds that as deflection increases the accident rate decreases until it reaches a "deflection angle" of 40 degrees corresponding to a 30 km/h circulation speed, then the accident rate remains low. Hydén and Várhelyi (*23*) show that a lateral displacement of 2 meters (deflection) is enough to reduce entry speeds to its lowest.

It seems that the inscribed circle diameter should not be too big and should not be larger than e.g. two times the central island diameter. Studies (*2, 30*) show that as the inscribed circle diameter / central island diameter -ratio increases the number of accidents between entering and circulating vehicles increases. This means that increasing width of circulation increases accident rate. Jensen (*1, 32*) finds that the best safety level is when the inscribed circle diameter / central island diameter -ratio is about 1.4. Spahn and Bäumler (*33*) find that single-lane roundabouts in rural areas with an inscribed circle diameter of less than 40 meters have accident rates that are 40-45 % lower than roundabouts with diameters of 40 meters or more. Rodegerdts et al. (*13*) find that as the inscribed circle diameter increases the number of accidents between exiting and circulating vehicles increases.

Studies show that a circulation lane of 6-8 meters at single-lane roundabouts provide the best safety. Spahn and Bäumler (*33*) find that a circulation lane width of up to 8 meters is safer than those with wider width. Rodegerdts et al. (*13*) show that as circulating width increases the number of accidents between exiting and circulating vehicles increases. Jørgensen and Jørgensen (*4*) find that 7-8 meters wide circulation lanes including truck aprons for single-lane roundabouts in urban areas seem to provide the best level of safety. Jensen (*1, 32*) finds that the best safety level is when a circulation lane is about 6.0-7.5 meters at single-lane roundabouts. Harper and Dunn (*34*) show that as width of circulation increases the accident rate increases.

Studies show deviating safety impacts of bypass lanes. Daniels et al. (*35*) find that bypass lanes (right-turn exclusive lanes) at roundabouts increase the number of accidents. Jensen (*36*) finds that bypass lanes improve safety at multi-lane roundabouts, but do not affect safety at single-lane roundabouts.

Studies (*13, 30, 37*) show that as the angle between arms increases the number of accidents between entering and circulating vehicles decreases. Jensen (*1, 32*) finds that as the difference between the smallest and largest angle between arms in a roundabout becomes smaller the level of safety becomes better. Harper and Dunn (*34*) show that increasing chord distance (measured from tip to tip of splitter islands) decreases the number of accidents between entering and circulating vehicles but increases the number of sideswipe accidents.

Spahn and Bäumler (*33*) find that tangential approaches to single-lane roundabouts in rural areas have a 30-40 % lower accident rate compared to radial approaches. Jensen (*1*) shows that triangular splitter islands (tangential approach) provide the best safety at single-lane roundabouts in urban areas.

Studies show that the width of entry and exit lanes should not be too narrow and not too wide in order to provide good safety. Maycock and Hall (*30*) show that as width of entry at yield line increases the number of accidents between entering and circulating vehicles increases and at the same time the number of accidents between approaching vehicles decreases. For undeflected entries this means that the total number of accidents increases as width of entry at yield line increases. For entries with maximum deflection the width of entry does not seem to affect the total number of accidents. Aagaard (*38*) finds that the accident rate in urban single-lane roundabouts increases as entry width increases. Rodegerdts et al. (*13*) find that as entry width increases the number accidents between entering and circulating vehicles increases. Jensen (*1*) finds that 3.4-4.3 meter wide entry lanes and 3.8-4.7 meter wide exit lanes (measured about 7 meters away from the inscribed circle) provide the best level of safety at single-lane roundabouts.

Wide approaches seem to increase the number of accidents at roundabouts. Maycock and Hall (*30*) show that as the width of the approaching road increases the number of single-vehicle accidents increases. Rodegerdts et al. (*13*) find that as the width of the approaching road increases the number accidents between approaching vehicles increases.

Studies show that motor vehicle speeds should not be higher than around 30 km/h at single-lane roundabouts in order to be safe. Turner et al. (*39*) find that the number of approach accidents increases with increasing speed limit. They show that the number of accidents between entering and circulating vehicles increases with increasing entry and circulation speed. Arndt (*40*) finds that the accident rate increases with increasing approach and entry speeds and speed differences at roundabouts. Chen et al. (*41*) estimate roundabout accident models with/without a variable for the average of entry, circulation and exit speeds – called inside average speed (IAS). They find that the accident model with the IAS speed variable is far better than a model without the variable. IAS speed correlates with inscribed circle diameter and entry width. Jensen (*1*) finds that when IAS is about 24-28 km/h then the level of safety is best at single-lane roundabouts.

Studies show that the type of bicycle facility at roundabouts influence bicycle safety. Brilon (*20*) finds that marking cycle lanes next to the circulation increased bicycle accidents from 1 to 8 at three roundabouts. Schoon and Minnen (*7*) show that roundabouts with separate bicycle paths are safer than roundabouts with marked cycle lanes or no bicycle facility at high traffic volumes. Brüde and Larsson (*27*) find that it is safer at higher traffic volumes with separate bicycle paths and special cycle crossings instead of cycling in the circulation with motor vehicles. Sakshaug et al. (*42*) show that roundabouts with separate bicycle paths and special crossings are safer than roundabouts without bicycle facilities. Daniels et al. (*43, 44*) find that roundabouts with marked cycle lanes next to the circulation are less safe for cyclists than roundabouts without bicycle facilities and roundabouts with separate cycle paths are safer than roundabout with no bicycle facilities. Jørgensen (*2*) shows that the injury rate is lowest at roundabouts with cycle tracks next to the circulation and a bit higher at roundabouts without bicycle facilities and highest at roundabouts with marked cycle lanes. Jensen (*24*) finds that separate cycle paths are safer than no bicycle facility and that marked cycle lanes are least safe. He also finds that cycle tracks next to the circulation are safer than no bicycle facility and less safe than separate cycle paths and finds that marking colored cycle crossings or colored cycle lanes worsen safety.

Jensen (*1*) uses meta-analysis to combine studies of safety effects of bicycle facilities at roundabouts in Denmark, Sweden and the Netherlands see table 2. Table 2 shows that marking cycle lanes next to the circulation increases the number of bicycle injuries by about 33 %. A cycle track with a curb to the circulation (circulating cyclists have priority over entering and exiting vehicles) reduce bicycle injuries by 26 % and a separate bicycle path (circulating cyclists have no priority) reduce bicycle injuries by 84 %.

TABLE 2 Results from Meta-Analyses of Safety Studies of Roundabouts with Different Bicycle Facilities. Baseline is a Roundabout with No Bicycle Facility. Based on 1,156 Fatal and Non-Fatal Injuries among Pedal Cyclists

Type of accident / injury	Included studies	Type of bicycle facility	Best estimate of safety effect	95 % confidence interval
Fatalities and injuries among pedal cyclists	*2, 6, 7, 19, 45*	Marked cycle lane	+33 %	+12 % ; +58 %
	2, 19	Cycle track	-26 %	-56 % ; +24 %
	6, 7, 19, 45	Separate bicycle path	-84 %	-91 % ; -69 %

Studies (*19, 35*) show that zebra crossings at roundabouts increase the number of accidents. Harper and Dunn (*34*) show that increasing distance between yield line and pedestrian crossing increases the number of pedestrian accidents.

Spahn and Bäumler (*33*) find that rural single-lane roundabouts with lighting have a 43 % lower accident rate than comparable roundabouts without lighting.

HEIGHT OF CENTRAL ISLAND

Studies (*1, 30*) find no relation between accident rate and visibility around the central island. Schurr and Sanchez (*46*) show that trees on central islands at single-lane roundabouts reduce motor vehicle approach speeds significantly, but do not change circulation speed. Daniels et al. (*35*) find that roundabouts with central islands more than 0.5 meters high have a lower accident rate than roundabouts with lower central islands. Jensen (*32*) finds that the height of the central island is not related significantly to accident density at single-lane roundabouts.

In the following further details about the safety effects of converting intersections to single-lane roundabouts with various central island heights are elaborated. These details are based on a study by Jensen (*24*) who describes the methodology of estimating safety effects. Jensen (*24*) finds that converting intersections to 265 single-lane roundabouts result in better safety effects when the central island is 2 meters or higher compared to lower islands.

The height is measured from the circulating lane pavement to the top of items at the center of the central island. The items have to be wide enough so a passenger car may hide behind it. Items may be sculptures, planting, landscaping, etc. Single-lane roundabouts in rural areas and large central islands tend to have higher central islands compared to roundabouts in urban areas and small central islands.

TABLE 3 Safety Effects on all Accidents of Converting Intersections to Single-Lane Roundabouts split by Central Island Height, Location and Central Island Diameter including Truck Apron. Note: N is the Number of Converted Sites with Accidents

CI height	Location	CI diameter	N	Before	Expected	After	Effect	Significant
0-1.9 m	Urban	3.5-19.9 m	50	172	111	118	+6 %	No
		20.0-39.9 m	36	202	124	106	-15 %	No
		40.0-60.0 m	2	10	5	7	+34 %	No
		Total	88	384	241	231	-4 %	No
	Rural	3.5-19.9 m	7	40	26	20	-22 %	No
		20.0-39.9 m	56	393	239	127	-47 %	Yes
		40.0-60.0 m	1	7	4	3	-19 %	No
		Total	64	440	268	150	-44 %	Yes
	Total		152	824	509	381	-25 %	Yes
2.0-10.0 m	Urban	3.5-19.9 m	1	2	1	0	-100 %	No
		20.0-39.9 m	21	120	71	48	-32 %	Yes
		40.0-60.0 m	0	-	-	-	-	-
		Total	22	122	72	48	-33 %	Yes
	Rural	3.5-19.9 m	1	8	6	3	-46 %	No
		20.0-39.9 m	48	367	220	91	-59 %	Yes
		40.0-60.0 m	8	43	31	29	-6 %	No
		Total	57	418	257	123	-52 %	Yes
	Total		79	540	329	171	-48 %	Yes
Total			231	1,364	838	552	-34 %	Yes

Conversions of intersections to single-lane roundabouts with 0-1.9 meters high central islands have resulted in an accident reduction of 25 %, whereas higher central islands resulted in a 48 % reduction, i.e. 23 percentage points difference, see table 3. Table 3 shows that safety effects are better in rural areas compared to urban, and safety effects for roundabouts with 20-40 meters central island diameters are better than roundabouts with smaller or larger diameters. For roundabouts with 20-40 meters central island diameters the safety effects in urban areas are accident reductions of 15 % with low and 32 % with high central islands. In rural areas the corresponding reductions are 47 % with low and 59 % with high central islands. So the breakdown of safety effects indicates that the difference in safety effects is not 23 but only 12-17 percentage points.

The height of the central island may arise due to trees and bushes, mound and knolls, sculptures and other structures. Trees and bushes are to some extent transparent, whereas the other items are solid. Central islands with high solid items produce the best safety effects both in urban and rural areas, see table 4. High solid central islands produce better safety effects than low solid central islands in both urban and rural areas. High transparent central islands only produce better safety effects than low transparent central islands in urban areas.

Roundabouts with high central islands produce better safety effects because the number of accidents between entering and circulating vehicles is much lower than at roundabouts with low central islands. This is particularly beneficial for pedal cyclists and car and truck drivers. Roundabouts with high central islands have more single-vehicle accidents and rear-end accidents than roundabouts with low central islands and this is worsening safety particularly for motor cyclists.

TABLE 4 Safety Effects on all Accidents of Converting Intersections to Single-Lane Roundabouts with 20.0-39.9 meters Central Islands including Truck Aprons split by Central Island Height, Transparency of Items on Central Island and Location. Note: N is the Number of Converted Sites with Accidents

CI height	Transparency	Location	N	Before	Expected	After	Effect	Significant
0-1.9 m	Transparent – planting, trees and bushes	Urban	24	134	83	78	-6 %	No
		Rural	24	185	120	48	-60 %	Yes
		Total	48	319	203	126	-38 %	Yes
	Solid – knolls, mounds, art, and structures	Urban	12	68	41	28	-33 %	No
		Rural	32	208	119	79	-33 %	Yes
		Total	44	276	160	107	-33 %	Yes
	Total		92	595	363	233	-36 %	Yes
2.0-10.0 m	Transparent – planting, trees and bushes	Urban	15	86	52	37	-29 %	No
		Rural	27	201	128	65	-49 %	Yes
		Total	42	287	180	102	-43 %	Yes
	Solid – knolls, mounds, art, and structures	Urban	6	34	19	11	-42 %	No
		Rural	21	166	92	26	-72 %	Yes
		Total	27	200	111	37	-67%	Yes
	Total		69	487	291	139	-52 %	Yes
Total			161	1,082	654	372	-43 %	Yes

SIGHT DISTANCES

Maycock and Hall (*30*) find that as the upstream approach and circulating approach sight distance from 15 meters back of yield line increases the number of single-vehicle accidents and accidents between approaching vehicles increases. Turner et al. (*39*) show that the number of "loss of control" accidents increases as the sight distance to upstream arm 10 meters back from yield line increases. Kennedy et al. (*37*) find that longer sight distances to the previous arm, next arm and opposite arm at mini-roundabouts both 4 and 50 meters from yield line increases the number of accidents. Campbell et al. (*47*) show that excessive sightlines contribute to higher driver speeds at roundabouts that potentially can lead to more loss-of-control, rear-end and entering versus circulating vehicle accidents. They refer studies of sight-screen installations that have reduced injury accidents by up to 46 %. Giæver (*48*) shows that roundabouts with high accident frequency had longer upstream approach and circulating approach sight distances than roundabouts with low accident frequency. Zirkel et al. (*49*) find for roundabouts with 25 mph speed limit that the accident rate is higher at roundabouts with long upstream and circulating approach sight distances compared to short sight distances. However they also show that for roundabouts with higher speed limits safety improves as sight distances get longer. They show that accident rate decreases as intersection sight distance increases. Johnson (*50*) finds that as upstream approach sight distance gets longer entry speed gets higher.

In Denmark, a road user must at 3 meters before the yield line be given sight to the area marked in grey as shown in figure 1. Jensen (*1*) measured how far from the yield line a road user actually got sight to this area, i.e. a combined upstream approach and circulating approach sight distance. This was done for all approaches in the 265 single-lane roundabouts that were part of the before-after safety study of converting intersections to roundabouts.

FIGURE 1 Minimum sight distances at 3 meters before yield line in Denmark.

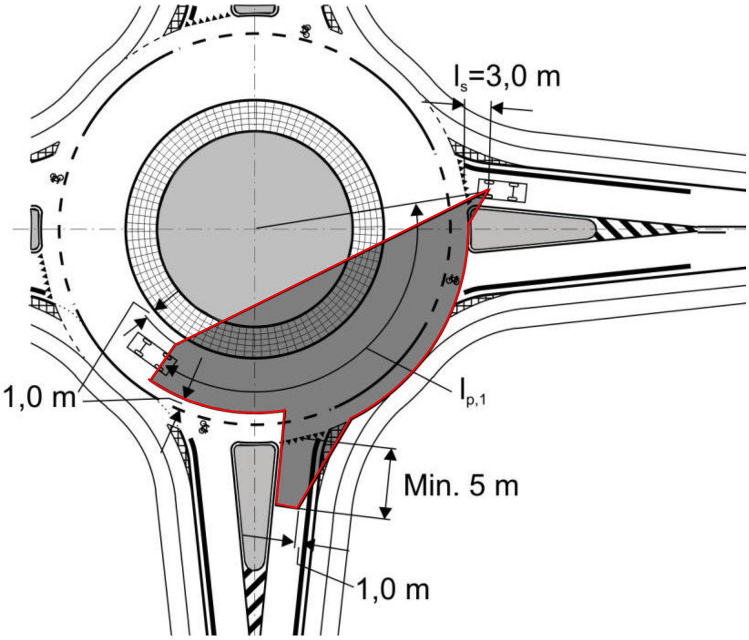

TABLE 5 Safety Effects on all Accidents of Converting Intersections to 4-armed Single-Lane Roundabouts split by Location and Average Approach Sight Distance. Note: N is the Number of Converted Sites with Accidents

Location	Approach sight distance	N	Before	Expected	After	Effect	Significant
Urban	5.0-15.0 meters	13	46	31	17	-44 %	Yes
	15.1-30.0 meters	25	104	69	78	+12 %	No
	30.1-50.0 meters	18	102	67	55	-18 %	No
	50.1-75.0 meters	17	82	42	22	-47 %	Yes
	75.1- meters	8	43	27	15	-45 %	Yes
	Total	81	377	236	187	-21 %	Yes
Rural	5.0-15.0 meters	1	11	5	4	-18 %	No
	15.1-30.0 meters	3	22	17	9	-48 %	No
	30.1-50.0 meters	19	166	108	67	-38 %	Yes
	50.1-75.0 meters	28	197	122	65	-47 %	Yes
	75.1- meters	44	303	173	90	-48 %	Yes
	Total	95	699	425	235	-45 %	Yes

Table 5 shows that approach sight distances do not seem to influence safety effects in rural areas. In urban areas safety effects for roundabouts with approach sight distances of 15-50 meters is worse compared to other sight distances. Analyses show that this is true for roundabouts of various central island diameters and heights. Detailed analyses show that it is particularly sight distances of about 17-40 meters in urban areas that results in poor safety effects. The poor safety effects are predominantly due to more single-vehicle and rear-end accidents at urban roundabouts with 15-50 meters approach sight distance.

PAVEMENT MARKINGS AND SIGNAGE

Worthington (*51*) shows that use of reflective block-paved chevrons on the central island in conjunction with lighting to full standards reduced approach speeds and single-vehicle accidents. Spahn and Bäumler (*33*) show that rural roundabouts with a 0.3 meter high beveled curb at the central island edge have a 15 % higher accident rate and more severe accidents than rural roundabouts without such beveled curb. Helliar-Symons (*52*) finds a 52 % accident reduction at roundabouts after yellow bars had been laid on approach lanes.

TABLE 6 Safety Effects on all Accidents of Converting Intersections to Single-Lane Roundabouts with 20.0-39.9 meters Central Islands including Truck Aprons split by Location, Presence of Edge Line to Central Island/Truck Apron and Width of Truck Apron. Note: N is the Number of Converted Sites with Accidents

Location	Edge line	Width of truck apron	N	Before	Expected	After	Effect	Significant
Urban	No edge line	0 meters	1	6	4	1	-73 %	No
		0.6-2.0 meters	10	52	28	24	-14 %	No
		2.1-3.4 meters	14	74	46	44	-3 %	No
		3.5-7.0 meters	4	20	12	14	+21 %	No
		Total	29	152	89	83	-6 %	No
	Edge line present	0 meters	1	2	2	2	+10 %	No
		0.6-2.0 meters	8	63	34	16	-53 %	Yes
		2.1-3.4 meters	9	41	24	12	-50 %	Yes
		3.5-7.0 meters	10	64	47	41	-12 %	No
		Total	28	170	107	71	-33 %	Yes
Rural	No edge line	0 meters	2	12	9	5	-44 %	No
		0.6-2.0 meters	9	67	42	11	-74 %	Yes
		2.1-3.4 meters	14	108	67	46	-31 %	Yes
		3.5-7.0 meters	4	22	15	8	-45 %	No
		Total	29	209	133	70	-47 %	Yes
	Edge line present	0 meters	1	10	7	5	-33 %	No
		0.6-2.0 meters	15	131	82	34	-59 %	Yes
		2.1-3.4 meters	42	305	179	79	-56 %	Yes
		3.5-7.0 meters	17	105	57	30	-47 %	Yes
		Total	75	551	326	148	-55 %	Yes

Jensen (*1*) recorded width of truck aprons at central islands and presence of white solid edge lines 10-30 cm wide marked between circulation and central island or truck apron. Table 6 indicates that marking an edge line do not produce better safety effects if there is no truck apron though accident figures are small. The table also shows that with a truck apron it seems safer to mark an edge line and as the truck apron gets wider the safety effects get worse. Detailed analyses indicate that an approximately 2 meters wide truck apron including an edge line is the safest design in both urban and to rural areas. The safety impact of the edge line in rural areas is small.

Jensen (*1*) recorded signs and pavement markings 20-500 meters from yield lines for roundabout approaches. Signs and markings consisted of warning signs (yield ahead and roundabout plagues), destination signs and warning pavement markings (yield ahead including rumble strips). Signs and markings were counted and the distances from the yield line to the sign/marking furthest away were recorded for each approach. If no sign or marking on the approach then distance was set to zero. Table 7 shows that as the number of signs and markings on approaches increases safety effects get better. It shows that as the distance from yield line to sign or marking furthest way increases safety effects get better in urban areas, whereas there is no significant relation between this distance and safety effects in rural areas. These relations between safety effects and the distance to and numbers of signs and markings exist for all central island diameters and heights.

TABLE 7 Safety Effects on all Accidents of Converting Intersections to Single-Lane Roundabouts split by Location, Average Number of Signs and Markings per Approach and Average Distance from Yield Line to the Sign or Marking furthest away. Note: N is the Number of Converted Sites with Accidents

Location	Average	Number or distance	N	Before	Expected	After	Effect	Significant
Urban	Number of signs and markings per approach	0	14	36	22	38	+70 %	Yes
		0.25-0.75	28	109	67	73	+10 %	No
		1	35	173	107	99	-7 %	No
		1.25-2	23	159	101	62	-39 %	Yes
		2.25-7	2	6	3	0	-100 %	No
	Distance from yield line to the sign or marking furthest away	0 meters	14	36	22	38	+70 %	Yes
		10-50 meters	27	96	59	75	+26 %	No
		51-100 meters	28	123	72	63	-13 %	No
		101-150 meters	21	153	104	78	-25 %	Yes
		151-200 meters	7	27	17	8	-52 %	No
		201-250 meters	5	48	26	10	-61 %	Yes
Rural	Number of signs and markings per approach	0.25-0.75	6	23	10	8	-24 %	No
		1	24	161	103	56	-45 %	Yes
		1.25-2	72	521	324	171	-47 %	Yes
		2.25-7	19	153	88	38	-57 %	Yes
	Distance from yield line to the sign or marking furthest away	10-50 meters	1	2	1	0	-100 %	No
		51-100 meters	6	23	13	10	-22 %	No
		101-150 meters	17	96	60	23	-62 %	Yes
		151-200 meters	34	267	169	94	-44 %	Yes
		201-250 meters	49	377	238	128	-46 %	Yes
		251-340 meters	14	93	44	18	-59 %	Yes

DISCUSSION

A high central island reduces sight to the opposite arm and circulating traffic furthest away. The paper shows that high central islands decrease the number of accidents between entering and circulating vehicles, but increase the number of single-vehicle and rear-end accidents.

This indicate that high central islands do not make approaching road users more aware of the roundabout, but directs more of entering road users attention towards the upstream approach and circulating traffic from the left.

It seems that car drivers who get sight to the upstream approach and to circulating traffic from the left about 17-40 meters before the yield line at urban roundabouts have safety problems. This phenomenon does not seem to exist at rural roundabouts. An explanation may be that approaching car drivers start to brake 20-40 meters before the yield line in urban areas but 70-90 meters before the yield line in rural areas. The problem in urban areas may arise when approaching car drivers start to brake and want to decide their entry speed at the same time as they get sight to the upstream approach and circulating traffic.

The research on relations between safety and truck apron at the central island and an edge line next to it is novel. More research is needed in order to find whether a 2 meter wide truck apron with a white solid edge line next to it actually is the safest option. The relations between safety and the number of signs and markings on approaches to roundabouts in this paper are strong. More research is needed to identify the safest types of signs and markings and the safest lineup of signs and markings.

CONCLUSIONS

The main conclusions of the research reported in this paper can be summarized in the following points:

- A high central island at single-lane roundabouts improves safety. This seems true when the height at the center of the central island is about 2 meters or more above the circulation and not transparent. High transparent planting like trees and bushes only seem to provide better safety at urban roundabouts.
- If the upstream and circulating approach sight to an urban single-lane roundabout is given about 17-40 meters before the yield line then there seems to be a considerable safety problem.
- It seems that a 2 meters wide truck apron around the central island is safer compared to a wider or narrower truck apron at single-lane roundabouts. An edge line between the truck apron and the circulation improves safety at urban roundabouts, whereas it is uncertain if this is the case at rural roundabouts.
- Signs and markings on the approaches to single-lane roundabouts seem to improve safety. More signs and markings relate to better safety and as signage and marking starts further away from the roundabout then safety also become better particularly in urban areas.
- More research about height of central islands, sight distances, signs and markings at roundabouts is important because these design features may be highly cost-effective in preventing accidents.

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