Effectiveness of road safety measures at junctions

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Abstract
The objective of this paper is the assessment of the effectiveness of road safety measures at junctions. In particular, the paper investigates the effectiveness of various junction layout treatments (conversion of junctions to roundabouts, redesigning of junctions, changes of the junction angle, staggering of junctions, reduction of gradients on approach, increase of sight triangles and channelisations) or traffic control interventions (implementation of 'yield' or 'stop' signs, the implementation or the upgrade of traffic signals) aiming to reduce road accidents and fatalities. An exhaustive review of the literature was carried out, in order to summarise the existing research findings with respect to safety effects, non-safety effects (e.g. traffic or environmental effects), and cost-effectiveness assessment of the examined measures, with focus on the estimation of the cost-benefit ratio of the measures in a reliable way. Particular emphasis was put on the identification of the implementation conditions that are associated with the magnitude of the effects in each case. Moreover, the ranges of implementation costs per unit of implementation were estimated. The results of the present research suggest that road safety measures implemented at junctions are among the most promising road safety measures, given that they are generally associated with very satisfactory cost-benefit results. However, it is recommended that cost-benefit ratios and safety effects are always examined in conjunction with each other. Moreover, transferability of results among different settings or countries should be examined with particular caution.

Key-words: road safety measures; junction layout; traffic control; safety effect; benefit-cost ratio.

1. Objectives and methods

The choice of junction design and operational features depends upon several factors, whose relative importance varies between cases and needs to be assessed. These factors mainly include traffic safety, road type and function, number of concurring legs, traffic volume, design and operating speed, priority setting, available space, adjacent land use, network design consistency, environmental factors and cost (*1*) . The type of junction has to be suited to the road type, the environment and capacity, in order to maintain good readability both of the road and of the junction, as well as a satisfactory level of safety (*2*,*3*).

Nevertheless, more than 5,000 of fatalities in road accidents at junctions were recorded in Europe on 2008, corresponding to more than 20% of total fatalities. Especially in urban areas, fatalities at junctions correspond to 29% of total fatalities (*4*). In this context, the effectiveness of junction treatments aiming to improve road safety needs to be analysed, so that good practices at international level can be identified.

The objective of this paper is the assessment of the effectiveness of road safety measures at junctions. In particular, the paper investigates the effectiveness of various junction layout or traffic control interventions aiming to reduce road accidents and fatalities. More specifically, the road safety measures examined include a number of junction layout treatments, such as the conversion of junctions to roundabouts, redesigning of junctions, changes of the junction angle, staggering of junctions, reduction of gradients on approach, increase of sight triangles and channelisations. Moreover, the road safety measures examined include a number of traffic control treatments, such as the implementation of 'yield' or 'stop' signs, the implementation or the upgrade of traffic signals etc.

An exhaustive review of the literature was carried out, in order to summarise the existing research findings with respect to safety effects, non-safety effects (e.g. traffic or environmental effects), and cost-effectiveness assessment of the examined measures, with focus on the estimation of the cost-benefit ratio of the measures in a reliable way. From the results of this in-depth review, the minimum and maximum safety effects of the treatments were assessed, as well as the minimum and maximum cost-benefit ratio. Particular emphasis was put on the identification of the implementation conditions that are associated with the magnitude of the effects in each case. Moreover, the ranges of implementation costs per unit of implementation were estimated.

Although there are a great number of studies dealing with junction layout and traffic control issues, not many of them include the calculation of safety effects and benefit/cost ratios with their confidence intervals in the standard and recommended methodology. In the present research, only statistically significant results based on the standard methodologies are presented.

2. Effectiveness of junction layout treatments

2.1. Description

Junction layout treatments concern a broad range of measures, including junction type conversions and junction alignment improvements, such as converting junctions to roundabouts, re-designing junctions, staggered junctions and junctions channelisation.

Roundabouts are junctions with counter-clockwise (in right-driving countries) circulatory traffic. Roundabouts can improve traffic flow and road safety both in urban and rural areas, through a reduction of the traffic speeds, but also through the elimination or reduction of specific types of conflict points that typically occur at angular intersections (*1*) (see Figure 1). Roundabout specific configuration allows all traffic to come from one direction, with uniform yielding rules (e.g. give way to users already in the roundabout), whereas left turns in front of oncoming traffic are eliminated and travel speeds are reduced.

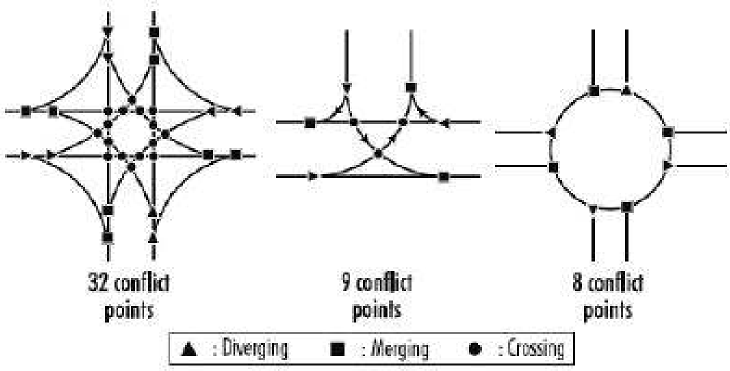

Figure 1. Conflict points of various junction types

Redesigning junctions may concern a change of the angle between roads (see Figure 2), changes to the gradients of the roads and / or any other additional measures that may improve sight conditions in the junction area (e.g. increase of sight triangles) (*1*).

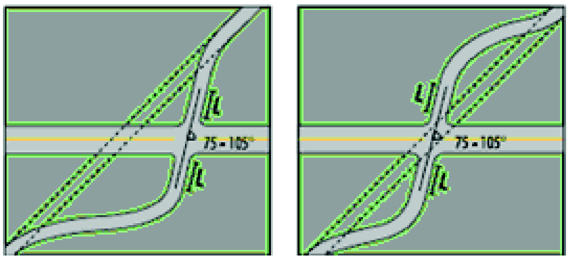

Figure 2. Junction re-alignment

Staggered junctions aim at reducing the number of conflict points at junctions (*2*) and can be constructed in two ways: left-right staggering and right-left staggering (see Figure 3). In general, four-arm junctions have higher accident rates than three-arm junctions, because they have more conflict points between the streams of traffic. One of the road safety treatments commonly used to reduce accidents at junctions is to stagger the junction (to convert a cross intersection into a pair of T-intersections) (*3*). These investments are mainly implemented in rural areas.

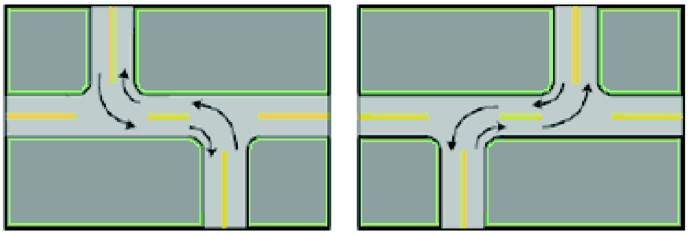

Figure 3. Junction staggering

Channelisation at junctions aims at segregating traffic flows from each other and reduces the area of conflict between different intersecting traffic streams, provide junction angles to give good visibility and define driving patterns and indicate which road has priority. It can be carried out by using traffic islands (physical channelisation) or road markings (painted channelisation), can range from minor to full channelisation and can include left-turn, right-turn and passing lanes, depending on the type of the junction that is treated (*1*). An example of partial physical channelization of a four-arm junction (i.e. installation of traffic islands on the main road) is presented in Figure 4. Additionally, the installation of medians or widening existing ones can also be considered as channelisation treatment, as well as the implementation of shoulders on the secondary branches.

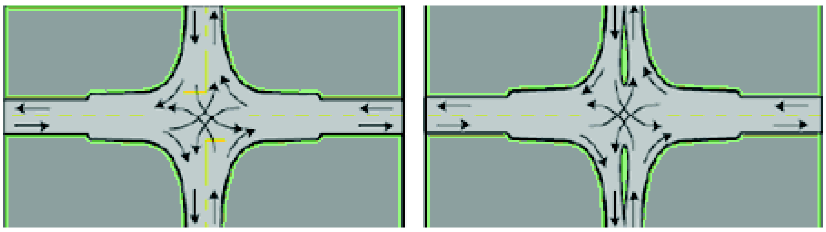

Figure 4. Junction channelization: before (left panel) and after (right panel) the installation of traffic islands on the main road.

The results of the analysis of the effectiveness of junction layout treatments are described in detail in the following section, whereas a summary of findings is presented in Table 1.

2.2. Safety effects

Important safety effects are associated with the development of roundabouts (*5*). In particular, statistically significant results indicate that:

- Converting stop-controlled junctions to roundabouts may result in 31% reduction of injury accidents for T-junctions and 41% reduction of injury accidents for crossroads (*2*).

- Converting traffic-signal-controlled junctions to roundabouts may result in 11% reduction of injury accidents for T-junctions and 17% reduction of injury accidents for crossroads (*2*).
- Converting stop-controlled single-lane urban and rural junctions to roundabouts may reach around 75% reduction of injury accidents and around 85% reduction of all accidents (*6*).
- Converting traffic-signal-controlled single-lane rural junctions to roundabouts may result in around 35% reduction of injury accidents and 75% reduction of all accidents (*6*).
- Converting any type of urban junction to a roundabout may result in around 45-50% reduction of injury accidents (*7*).

In general, the installation of roundabouts results in substantial reductions to road accidents. This effect is systematically higher for fatal or serious injury accidents and lower for minor injury accidents. In some studies, the negative safety effect of roundabouts on material damage only accidents was identified. Moreover, roundabouts appear to have lower safety effect when replacing traffic-signal controlled junctions, than when replacing yield controlled junctions.

Research results concerning junction re-designing are in some cases uncertain; however, following meta-analysis (*2*) based on examples from several countries, it can be deduced that:
- An angle of less than 90 degrees gives the fewest injury accidents and the opposite appears to be the case for material damage only accidents. Re-designing a junction of an angle less than 90º to an angle of 90º, may increase injury accidents by 80%. On the contrary, re-designing a junction of an angle of 90º to an angle of more than 90º, appears to bring a reduction of injury accidents by 50%
- A change in gradient on approaches to the junction from more than 3% to less than 3% appears to be associated with a (marginally significant) reduction of the number of injury accidents of 17%, but with an increase of the number of material damage only accidents.
- Meta-analysis results (*2*) indicate negative safety effects of improving sight triangles at T-junctions (30% increase of injury accidents), and positive safety effects at 4-leg junctions (50% reduction of injury accidents). On the other hand, in the Highway Safety Manual (*8*), a safety benefit of 73% is associated with increases of sight triangles.

The effect of staggered junctions appears to strongly depend on the proportion of traffic of the secondary (minor) road at the crossroads before the staggering. Only when traffic of the secondary (minor) road is important can the number of injury accidents be significantly reduced. Staggered junctions may result in 33% reduction of injury accidents when the traffic on the minor road is normal or heavy (*2,3*)

In general, the results concerning staggered junctions should be considered with some caution, given the small number of available studies and the important number of factors affecting the safety effect. For instance, the safety effect of staggered junctions may be partly due not to the staggering itself, but to the introduction of median islands, right-turn lanes and other forms of channelisation usually applied when implementing the staggering.

The majority of the various forms of channelisation appear to have a more important effect on the number of accidents at crossroads than at T-junctions, although some of the existing results are rather uncertain. There is a tendency that the more comprehensive the channelisation methods are, the more important the effect on accidents (*9*). In particular, on the basis of meta-analysis (*2*):
- Introducing a painted left-turn lane on T-junctions may reduce injury accidents by 22%. The effect increases to 27% when the left-turn lane is physical.
- Introducing a physical left-turn lane on 4-leg junctions appears to reduce injury accidents by around 4%. The effect is negative (injury accidents appear to increase) when the left-turn lane is painted.
- Full physical channelisation (left- and right-turn lanes, medians etc.) may reduce injury accidents at 4-leg junctions by 27%.

- On the contrary, full physical channelisation at T-junctions is not associated with positive safety effects.

Other research, however, reports more positive and consistent results (*10*):
- Introducing a painted left-turn lane on rural stop-controlled T-junctions may reduce injury accidents by 44%. The effect is reduced to 15% when the junction is signalised. The respective effects on urban T-junctions are 33% and 7% respectively
- Introducing a painted left-turn lane on rural stop-controlled 4-leg junctions may reduce injury accidents by 28%. The effect is reduced to 18% when the junction is signalised. The respective effects on urban T-junctions are 27% and 10% respectively

2.3. Other effects

Roundabouts are generally characterised by lower travel speeds; however, drivers experience reduced waiting times in roundabouts, mainly due to the fact that they tend to accept smaller traffic gaps when crossing the roundabout. The overall improvement in mobility depends on the distribution of vehicles arrivals and the daily variations in traffic conditions; it is therefore difficult to establish a general rule. It has been found, though, that waiting times at signalised junctions are reduced heavily by the construction of a roundabout (*7*).

Re-designing junctions may improve mobility, to the extent that such changes improve sight triangles and the various features of the approaches to the junctions; however, such effects are difficult to consider in a generalised way.

Staggered junctions may be associated with different mobility effects. Right-left staggered junctions induce shorter travel times than both left-right staggered junctions and four-leg junctions, in the sense that drivers coming from the minor road have to give way to only one traffic stream, i.e. when turning to the right on to the main road (*11*). Recent research (*2*) estimated that, for an hourly traffic volume of 1,000 vehicles, the difference in waiting times between right-left staggering and left-right staggering is around 15 seconds per vehicle, whereas others (*3*) suggest that these time savings may reach 20 seconds per vehicle, when the entering flow are higher than 2,300 vehicle/h.

Moreover, it appears that mobility effects of channelisation are largely dependent on the amount of traffic on the main road; channelisation seems to reduce delays only when both the amount of traffic going straight and the amount of traffic turning left are high (*12*).

Concerning emissions, a reduction may be expected when replacing traffic-signal controlled junctions by roundabouts, and an increase when replacing yield-controlled junction by roundabouts. Again, no general conclusion can be drawn on this issue and it is recommended to examine these effects on case-specific basis. On average, emissions (CO and NOx) at roundabouts replacing non-signalised junctions may increase by between 4 and 6%, while a roundabout replacing a signalised junction may lead to a reduction by between 20 and 29%. The noise level is also reduced at junctions that are replaced by roundabouts (*7*). Another study also gave very positive performance results for a roundabout compared with a traffic signal junction, and it was found that the average driving speed through the junction in one direction could be increased by 50%, and as a result of this, emissions per vehicle could be decreased by 35% (*13*).

2.4. Implementation Costs

The costs of roundabout development may range from 450,000-1,300,000 €. Converting a T-junction to a roundabout is estimated at around 650,000 €, whereas the respective costs for four-leg junctions is estimated at around 450,000 €.

The costs of re-designing junctions may vary significantly for different types of treatment. Researchers report that the costs for a complete reconstruction of a junction in Norway are estimated at around 785,000 € in 1995 prices. Sight triangles improvements in Sweden are estimated at around 6,800 € (1980 prices) per junction, however the range of costs largely depends of the extent of the treatments (*2*).

Staggering junctions imply the construction of at least one new intersection. The cost of a staggered junction in Norway is estimated to range from 130,000 -1,300,000 million €.

Indicative costs for various forms of channelisation for Norway, indicate that 50% local variations may be expected, from 65,000 € (left-turn lane at T-junction) to 1,650,000 € (full channelisation at four-leg junction).

2.5. Cost-benefit (B/C) ratio

Benefit / Cost ratios of converting junctions to roundabouts in Norway are estimated at a range from 1.80:1 (T-junctions) to 2.20:1 (4-leg junctions) (*2*). Moreover, the ROSEBUD Handbook (*14*) provides respective results for urban areas for Norway at 1.23-8.61:1, and in the Czech Republic at 1.5:1.

With respect to junction re-alignment, results suggest that junction re-alignment related treatments shall be cost-effective in Norway if their costs are lower than 70,000 €, whereas staggered junctions shall be cost-effective if the investments costs are lower than 650,000 € (*2*)

Channelisation treatments are also expected to be cost-effective, although no results are available. Indicative examples for Norway suggest that minor channelisation of 4-leg junctions are expected to have a Benefit / Cost ratio of around 2.7:1, whereas full channelisation of 4-leg junctions are expected to have a Benefit / Cost ratio of around 1.1:1 (*2*).

3. Effectiveness of traffic control at junctions

3.1. Description

Traffic control at junctions aims to increase safety, improve traffic flow and simplify drivers' decision-making. At uncontrolled junctions, road safety problems are encountered in terms of increased accidents (material damage only and/or injury). The rule of giving way to traffic from the right applies for most (right-driving) countries for uncontrolled rural junctions; however, different traffic and priority control schemes can be applied for the purpose of improving road safety at junctions. Traffic control at junctions was found as one of the most promising investments for the improvement of road safety (*15*). These include the implementation of 'yield' signs, 'stop' signs or traffic signals and the upgrade of traffic signals

Within this framework, the measures shall be examined in two ways: first, when introduced at an uncontrolled junction and, second, when replacing a previous type of traffic control at a junction. As regards the upgrade of traffic signal control, it is noted that advanced schemes (e.g. user- or vehicle- actuated traffic signals, network coordinated traffic signal control etc.) are not examined.

'Yield' signs at the approaches of a junction, together with appropriate road markings, are the simplest traffic control scheme aiming to improve giving-way.

'Stop' signs (two-way or all-way) intend to give drivers more time to observe traffic conditions at the junction and yield accordingly. In two-way stop junctions, drivers on the minor road should give way to drivers on the major road. In all-way stop junctions, the first-in / first-out rule applies (i.e. whoever arrives first, goes first).

Traffic signal control at junctions separates different traffic flows. Traffic signals can be either time-controlled (with a fixed number and duration of phases) or vehicle- (or user-) actuated (the length of phases is optimised in relation to the number of vehicle arrivals at the junction or the number of pedestrians waiting, up to a certain maximum length). It is also possible that phases are shared between different traffic flows (e.g. right-turning drivers with pedestrians, or left-turning drivers with oncoming traffic). It is noted however that traffic signal control is mostly implemented in urban areas.

Moreover, an upgrade of traffic signal control may include redesigning of the number and duration of phases, reduction or elimination of shared phases, establishment of user- or vehicle-actuated phases, and so on.

The results of the analysis of the effectiveness of junction layout treatments are described in detail in the following section, whereas a summary of findings is presented in Table 2.

3.2. Safety effects

Traffic signal control at junctions is associated with significant positive road safety effects. According to the international experience, there is a small tendency towards higher safety effects of more advanced traffic control schemes.

According to a meta-analysis of results from Nordic countries, USA and Australia (*2*), only a small tendency towards accidents decrease is associated with the implementation of 'yield' signs at uncontrolled junctions; the results of the available studies are rather uncertain and the findings can not be fully validated statistically.

On the contrary, implementation of 'stop' signs at uncontrolled junctions appears to have an important safety effect. Replacing traffic signals with 'stop' signs improves road safety on one-way roads. More specifically:

- Introducing one-way 'stop' signs at T-junctions may reduce injury accidents by around 20% (*2*)
- Introducing two-way 'stop' signs at four-leg junctions may result in a significant reduction of injury accidents by 35%, while introducing all-way 'stop' signs at four-leg junctions may result in a respective reduction of 45% (*2*)
- Replacing traffic signals by 'stop' signs on urban one-way roads may result in a reduction of injury accidents by 24%, and a reduction of pedestrian accidents by 18% (*16*)

Implementation of traffic signal control appears to have positive effects on road safety outcomes. The related figures for T-junctions are somewhat lower than the ones for four-leg junctions, though. In particular:

- Introducing traffic signals at T-junctions may reduce injury accidents by around 15% (*2*)
- Introducing traffic signals at 4-leg junctions may reduce injury accidents by around 30% (*2*)
- Introducing traffic signals at 4-leg junctions may reduce rear-end accidents by around 35% (*17*)

Upgrading existing traffic signal control, such as reorganising phases, is associated with positive safety effects, although some of the existing results are rather uncertain. These upgrades can be roughly classified into two large groups: the first group concerns changes in the duration of phases. The following statistically significant results are available:

- Re-timing traffic signals, in order to improve the phases, may reduce injury accidents at junctions by 12% and pedestrian accidents at junctions by 37% (*18*)
- Switching from fixed phases to vehicle- or user-actuated phase changes may reduce all accidents at junctions by 25% (*2*)
- Network coordinated traffic signals (e.g. "green wave") is associated with a reduction of injury accidents at junctions of around 20% (*2*)

The second group of treatments concerns changes in the number and type of phases, and the results are slightly more uncertain, however some specific trends can be identified (*2*):

- Introducing mixed phase pedestrian signals appears to marginally increase pedestrian accidents by 8%, whereas a separate phase pedestrian signal appears to reduce pedestrian accidents by 30%
- Introducing a left-turn phase is associated with a significant reduction of all accidents of 10%, which may reach 60% in the case of separate left-turn phase
- On the other hand, right-turn permission during the red signal may increase injury accidents by 50-70%. It is noted, however, that this procedure tends to be rarely implemented in most countries in the last few years.

3.3. Other effects

The implementation of 'yield' signs may bring an increase of travel speeds on the main road and a decrease in travel speeds on the minor road. In case of two-way 'stop' signs, drivers on the minor road experience some delay, whereas in case of all-way 'stop' signs, all drivers experience some delay.

Traffic control also increases waiting times at junctions; however, in case of junctions with a high amount of traffic, traffic control may improve the total waiting times of all traffic streams. Although there are specific studies quantifying these effects in specific cases, their magnitude depends on the road and traffic conditions in each case.

As regards environmental effects, an increase in noise and emissions is confirmed by several studies dealing with 'stop' signs implementation. However, environmental benefits are associated with the improvement of traffic signals operation. For instance, increasing cycle length or increasing the proportion of green time appears to significantly reduce pollution (*19*).

3.4. Implementation Costs

Obviously, the implementation and maintenance costs of 'yield' and 'stop' signs are much lower compared to the related costs of traffic signal control schemes. The costs of signposting and road markings in Norway is estimated at around 250-700 € per sign. The average cost of implementing traffic signal control at junctions is estimated between 50,000 € and 300,000 € depending on the size and the local conditions, whereas maintenance costs are estimated at 4,000 € per year (*2*).

3.5. Cost-benefit (B/C) ratio

Given the uncertainty in the safety effect of 'yield' signs, no reliable cost-effectiveness results are identified. As regards 'stop' signs, examples (*2*) show that the measure is cost-effective mainly in rural areas with low traffic. In particular, results indicate a Benefit / Cost ratio of 6.8:1 for rural T-junctions in Norway. However, cost-benefit ratio was found negative for urban 4-leg junctions, due to vehicle delays and negative environmental effects.

Traffic signal control appears to be cost-effective at crossroads only (*2*). On the contrary, traffic signals at 4-leg junctions were attributed a cost-effectiveness of 8:1. In ROSEBUD (*14*) a cost-benefit ratio of 1.25:1 was calculated for introducing traffic signal control at rural junctions in Israel.

Upgrading traffic signals in Norway is expected to have e cost-benefit ratio equal to 8.6:1 (*2*).

Table 1. Junction layout treatments - Summary of findings

Investment: junction layouts

Network: rural / urban

Sub-investments:
- converting junctions to roundabouts
- redesigning junctions
- changing the junction angle, staggered junctions, reducing gradients on approach, increasing sight triangles (mainly rural areas)
- junction channelisation

Maximum safety effect:

• converting junctions to roundabouts	(-88%)
• changing the junction angle	(-50%)
• channelisation at 4-leg junctions	(-57%)

  - the more extensive the channelisation, the highest the safety effect

Minimum (or negative) safety effect:

• channelisation at T- junctions	(+16%)
• reducing gradients on approach	(-17%)
• staggered junctions (low traffic on minor road)	

Max. C-B ratio:

• converting junctions to roundabouts	2:1 to 3:1
• redesigning junctions	3:1
• junction channelisation	2.5:1 (for minor channelisation)

Min. C-B ratio:
- high cost redesigning junctions
- high cost channelisation

Implementation costs per unit*:

• converting junctions to roundabouts	€ 450,000 - 1,300,000
• redesigning junctions	from € 1,100,000
• staggered junctions	€ 130,000 - 1,300,000
• junction channelisation	€ 25,000 - 1,650,000
• development of mini roundabout	€ 12,000

Other effects:
- improved mobility (except left-right staggered junctions, for channelisation only when traffic is high)
- effects on noise and emissions
- in some cases the total junction area increases

Table 2. Traffic control treatments at junctions - Summary of findings

Investment: traffic control at junctions

Network: rural / urban

Sub-investments:
- implementation of 'yield' signs
- implementation of 'stop' signs
- implementation of traffic signals (mainly urban areas)
- upgrade of traffic signals (mainly urban areas)

Maximum safety effect:

- implementation of all-way 'stop' signs at 4-leg junctions (-45%)
- implementation of traffic signals at 4-leg junctions (-36%)
- upgrade of traffic signals (-37%)
  - introducing separate left-turn or pedestrian phases

Minimum (or negative) safety effect:

- implementation of traffic signals (+60%)
  - mixed pedestrian phase
  - right-turn permission during red signal

Max. C-B ratio:

• implementation of 'stop' signs	6.8:1 at rural T-junctions
• implementation of traffic signals	8:1 at 4-leg junctions
• upgrade of traffic signals	8.6:1

Min. C-B ratio:

• implementation of 'stop' signs	may be negative at 4-leg junctions
• implementation of traffic signals	may be negative at T-junctions

Implementation costs per unit:

• signposting	€ 250 – 700 per sign
• implementation of traffic signals	€ 50,000 – 300,000 per junction
	€ 4,000 annual maintenance costs

Other effects:

- increased delays (except for the major road when 'yield' or 'stop' signs are implemented on the minor road)
- increased noise and emissions (except green-wave traffic signals)

4. Summary and conclusion

The exhaustive review of the existing literature carried out within the present research revealed that sll junction treatments examined have high safety effects. Infrastructure-related investments have high implementation costs (e.g. roundabouts, staggering), whereas traffic control-related investments have low implementation costs (e.g. 'stop' signs). However, the relatively high implementation cost of some junction layout treatments (e.g. redesigning junctions) does not compromise their cost-effectiveness. Very satisfactory cost-benefit ratios were calculated in the large majority of such cases. Specific cases where the safety effects may be significantly reduced, or even eliminated, were also identified. For example, channelisation may have negative safety effects when applied to T-junctions, possibly due to an increase in travel speeds on the minor road, but has always has positive effects when applied to 4-leg junctions.

The minimum safety effects of junction layout treatments are associated with the reduction of gradients on approach, whereas maximum safety effects are associated with junction angle treatments. Moreover, there is some uncertainty regarding some aspects of sight triangle treatments. On the other hand, replacing junctions by roundabouts is associated with consistently positive safety effects and satisfactory cost-effectiveness.

As regards traffic control treatments, the minimum (and less statistically significant) safety effects are identified in the case of implementation of 'yield' signs. The safety effects of 'stop' signs vary according to the extent of the implementation (i.e. one-way or all-way stop, at T-junctions or at 4-leg junctions). The maximum safety effect achieved by introducing traffic signals at junctions is again associated with 4-leg junction treatments. Important safety effects are also achieved by upgrading traffic signals. However, this is so only when the upgrade leads to more efficient accommodation or separation of traffic flows (e.g. re-timing of traffic signals, introduction of separate pedestrian phases, or the introduction of separate left-turn phases). These positive safety effects are associated with very satisfactory cost-benefit ratios.

The results of the present research suggest that road safety measures implemented at junctions are among the most promising road safety measures, given that they are generally associated with very satisfactory cost-benefit results. However, the overall cost-effectiveness of a junction road safety measure is not always in direct correlation with the safety effect. For instance, roundabouts have very high safety effects, which are not directly reflected in the cost-benefit ratios available. On the other hand, the cost-benefit ratios of traffic signals are higher than those of roundabouts, although the safety effects of traffic signals are much less impressive. Consequently, it is recommended that cost-benefit ratios and safety effects are always examined in conjunction with each other.

It should be stressed that the ranges of results identified in the present research can by no means be considered to be applicable to every application of these measures. Although the cases examined were relatively representative and the results quite consistent, it is always possible that the particularities of setting, context, and implementation features of a specific junction may produce results with varying degrees of difference. Therefore, thorough analysis on a case-specific basis is always necessary in order to optimise the effects of a measure in different countries or areas, by taking into account the extent of the implementation, the implementation period, and specific national or local requirements.

Finally, it would be most interesting to examine the combined effect of geometric and traffic control treatments at junctions. An even increased effectiveness would be expected, as a result of the combination of two cost-effective treatments. However, very few related results are available in the existing literature, and these mainly concern re-designing junction treatments of increased implementation costs i.e. converting junctions to roundabouts or interchanges *(20,21)*. Particular emphasis should be put on the evaluation of combined effects of low-cost junction treatments in future research (e.g. combining channelization with separate left-turn phases, combining staggered junctions with traffic lights installation etc.).

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