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A budget optimisation model for road safety infrastructure countermeasures

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Abstract: The requirements and modifications to the road infrastructure to achieve high levels of safety require different countermeasures that are not directly comparable considering their life span. It is felt that the effectiveness of a road safety programme highly depends on the best mix between capital and maintenance work measures. To this end, this article introduces a novel methodology that prioritises countermeasures by considering their effectiveness over their life span together with budget constraints, based on a mixed integer linear programming model with an objective function to maximise their economic safety benefits. To illustrate the application of the proposed model developed using the LINGO software, a case study from the Netherlands, Utrecht provincial roads, was used. The results show that this approach seems to enhance both the prioritisation and the number of countermeasures selected for implementation. Furthermore, the method can compute the minimum budget required to maximise the economic benefits from capital work measures. It may also prioritise road safety-related maintenance work programmes and offer a plan for capital works if funds are below the minimum budget. Consequently, this approach appears to enhance the non-life span approach due to an improved mix between capital and maintenance work programmes for road safety.

ABOUT THE AUTHOR

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PUBLIC INTEREST STATEMENT

Infrastructure-related safety improvement programmes are usually capital-intensive, requiring planning and management. The road network consisting of sections and junctions and despite being built to engineering standards will usually require improvements and modifications due to changes mainly in traffic volumes and added safety requirements. Consequently, different countermeasures that may be categorised as capital and maintenance will usually be required to improve the safety standards and deficient sections of the road. Arguably, the effectiveness of a road safety programme highly depends on the best mix between these two categories of countermeasures. However, obtaining the optimal combination between capital and maintenance measures in an infrastructure programme is one of the challenges in determining the effective use of countermeasures. This article introduces and develops a unique concept of grouping countermeasures with regard to their life span as part of the prioritisation procedure.
1. Introduction

Infrastructure-related safety improvement programmes are usually capital-intensive, requiring planning and management. Over its life span, the road network consisting of sections and junctions and despite being built to engineering standards will usually require improvements and modifications due to changes mainly in traffic volumes and added safety requirements. Because of these changes, different countermeasures will usually be required to improve the safety standards and deficient sections of the road. The countermeasures may be categorised as capital work and maintenance work. Arguably, the effectiveness of a road safety programme highly depends on the best mix between these two categories of countermeasures. However, obtaining the optimal combination between capital and maintenance works in an infrastructure programme is one of the challenges in determining the effective use of countermeasures (Elvik, 2014). Clearly, the prioritisation and selection techniques employed by the most advanced road safety management systems, such as the SafetyAnalyst (Harwood et al., 2010) and the International Road Assessment Programme (iRAP) model (iRAP International Road Assessment Programme, 2015), do not take into account the varying categories of measures, and therefore, this may produce biased results. Furthermore, road safety budgets are usually not sufficient and always suffer cuts and diversions to handle emergencies and other priorities. This may lead to a need for a prioritisation methodology capable of handling budget constraints. Additionally, by considering the above categorisation of countermeasures, optimal allocation of resources between these two categories is equally necessary. To date, the use of economic analyses tools, such as cost-benefit analysis and cost-effectiveness, may provide important insights to countermeasure ranking and selection but seem to be ineffective in handling budget allocation problems (Persaud & Kazakov, 1994). For example, in a constrained budget, selecting countermeasures based on a descending order of benefit-to-cost ratio (BCR) until the budget is exhausted may not yield sustainable and optimal results (Jiang & Sinha, 1990). While previous budget optimisation models (Melachrinoudis & Kozanidis, 2002; Mishra & Khasnabish, 2012; Saha & Ksaibati, 2016) allocated resources amongst measures, highways, intersections or black spots, none of them addresses this specific problem. Certainly, without categorising measures, it is possible to preclude the selection of several countermeasures that may enhance a programme’s effectiveness within the budget constraints. An optimisation technique that considers the lives of countermeasures would also improve the sustainability of their assumed economic benefits. In the scholarly literature (Elvik, 2014; Van Uden & Heijkamp, 1995; Weber & Jahrig, 2010), the road safety countermeasures are categorised as short term, medium term and long term based on their service life but without a proper distinction with regard to the budget heads used to fund the implementation of the countermeasures.

A number of researchers (Mahmud et al., 2014; Tziotis, 2011) tentatively grouped road safety countermeasures as capital (long term) and maintenance (short term). Azmi and Evdorides (2019) demonstrated their implementation under a broader road development programme. Subsequently, this study develops the concept of road safety countermeasure prioritisation by considering an optimisation method that takes into account both their lives and the available funding to implement a road safety infrastructure improvement programme.

2. Literature review

Optimisation techniques have been widely applied in operations research, manufacturing, management, transportation engineering and finance. In road safety, dynamic programming (Brown, 1980), linear programming (Behnood & Pino, 2020; Kar & Datta, 2004; Saha & Ksaibati, 2016) and integer programming (Abdolmanafi & Karamad, 2019; Melachrinoudis & Kozanidis, 2002; Mishra & Khasnabish, 2012) techniques have been applied. Dynamic programming is a technique that solves a complex problem through a sequence of simpler sub-problems. Linear programming technique
expresses resource allocation problems mathematically in the form of linear equations and inequalities. Integer programming is an optimization technique in which all the variables are restricted to integers. The trend shows the recent application of linear and integer programming, or both, and more specifically, the use of the faster and advanced branch-and-bound technique. Melachrinoudis and Kozanidis (2002) developed a mixed integer allocation model for discrete (at specific points on the road network) and continuous (over the length of the road) improvements to maximise the reduction in the expected number of accidents. Kar and Datta (2004) used a linear programming technique for allocating resources in the state of Michigan to maximise the benefits of reducing total crashes. Similarly, Behnood and Pino (2020) developed a model to minimise a cost-effectiveness index excluding property damage only (PDO) crashes. An optimisation model by Mishra and Khasnabid (2012) allocated resources to maximise monetary benefits due to saved crashes at urban intersections. Another model developed for the best mix of countermeasures to improve black spots by Soha and Ksaibati (2016) allocated resources by maximising benefits in terms of reduced overall crash frequency but ignored PDO crashes. As seen with all these models, allocation of resources is mainly to selected measures, black spot areas, highways, cities or locations with no consideration of the lives of countermeasures, their funding or an entire road network in a comprehensive and optimised manner.

3. Method and proposed model

In computing the economic benefits, investment appraisal models may consider the reductions in the number of crashes or casualties as the safety benefits due to implementation of countermeasures (Byaruhunga & Evdorides, 2021). However, according to Byaruhanga and Evdorides (2022), in any investment appraisal model, it seems advantageous to consider the number of crashes instead of casualties and more so if PDO crashes are included in the analysis. For this reason, this study uses the number of all crashes together with the crash unit rates to determine the economic benefits instead of using casualty numbers. The optimisation model presented hereafter seeks to determine the optimal expenditure between capital and maintenance works and to maximise the economic benefits under a constrained budget. Its objective function (Z) in Equation 1 maximises the economic safety benefits due to reductions in fatal, serious, slight and PDO crashes. These are the monetised benefits computed at the end of the appraisal period taking into consideration discounting.

\[ Z = \text{Max} \sum_{i=1}^{N} \sum_{k=1}^{K} \left[ \left( f_{i}^{c} s_{i}^{c} + s_{i}^{s} + s_{i}^{c} + s_{i}^{l} + s_{i}^{p} + \text{PDO}_{i}^{c} \right) x_{i} \right] \]

where \( f_{i}^{c} \), \( s_{i}^{c} \), \( s_{i}^{s} \) and \( \text{PDO}_{i}^{c} \) represent fatal, serious injury, slight injury and PDO crash savings, respectively, for capital work measure \( i \) after project execution. \( f_{c}, s_{c}, s_{l} \) and \( PDO_{i} \) are the crash unit costs for fatal, serious injury, slight injury and PDO crashes, respectively. Similarly, \( f_{i}^{m}, s_{i}^{m}, s_{i}^{l} \) and \( PDO_{i}^{m} \) represent fatal, serious injury, slight injury and PDO crash savings respectively for maintenance work measure. The main constraint of the model is the total budget (B) given by:

\[ \sum_{i=1}^{N} \sum_{k=1}^{K} \left( C_{i}^{c} + C_{i}^{m} \right) x_{i} \leq B \]

\( N_{c}^{m} = N_{m}^{m} \)

\( X_{i} \in \{0, 1\} \)

\( X_{k} \in \{0, 1\} \)
The second constraint (Equation 3) ensures a mix between measures from the two categories. \( N_s \) and \( N_m \) are the number of selections made for capital and maintenance work measures, respectively, within the available budget (B). \( C_s \) and \( C_m \) are the discounted costs for capital work measure \( i \) and maintenance work measure \( k \), respectively. \( N \) and \( K \) represent the total number of capital and maintenance work measures, respectively. \( X_i \) and \( X_k \) are binary decision variables (1 if selected, otherwise 0).

Nowadays, optimization models can easily be developed using computer software such as Premium Solver Platform (Jiang, 2010), General Algebraic Modelling Systems (GAMS; Calasan et al., 2021) and LINGO (LINDO, 2020). LINGO has a remarkable popularity and is currently one of the most powerful and user-friendly software used since its inception in 1980s. Accordingly, in this study, LINGO software developed by Linear Interactive and Discrete Optimizer (LINDO) systems is utilised to run the developed model.

### 3.1. Model application

The practical application of the newly developed optimisation model is during the prioritisation step of an entire roadway safety management process. Therefore, any appropriate methodology may be adopted during network screening, diagnosis, countermeasure selection, as well as economic appraisal provided benefits and life cycle costs are established for each countermeasure for the analysis period. The key parameters required to run the model are the countermeasures grouped into two categories with regard to their life span together with their individual life cycle costs and economic safety benefits. To illustrate the application of the proposed model, a case study, part of the 20-year infrastructure improvement programme taken from iRAP International Road Assessment Programme (2021) for the Netherlands (Utrecht 2014 Provincial Roads), developed using the European Road Assessment Programme (EuroRAP) and the ViDA software, is used. Provincial roads that contribute 6% of the total Dutch network were among the most unsafe roads, with the risk of a serious accident five times higher in comparison to the national road network (ANWB, 2013). Consequently, in 2012 and 2013, the Royal Dutch Touring Club (ANWB) assessed these roads using EuroRAP methodology to recommend effective road safety improvements to prevent these accidents. The results of the assessment showed that over 65% of Utrecht provincial road network (332 km) had a rating of two stars (unsafe conditions). Therefore, the test data represented realistic and effective countermeasures based on these results to improve the assessed road network to a minimum safety level of three stars (safe condition). iRAP is a casualty-based model that considers only two severity levels (fatalities and serious injuries) that may underestimate economic safety benefits (Byaruhanga & Evdorides, 2022). As a result, a more accurate approach that uses crash numbers instead of casualty numbers and considering four severity levels (fatal, serious injury, slight injury and PDO) is preferred in this work. Consequently, part of the Utrecht infrastructure programme was modified, and countermeasures with life years more and less than 10 years were categorised as capital (C) and maintenance (M) work measures, respectively, as shown in Table 1.

Further analysis of the original data established that a total of €71 million was required to implement countermeasures to yield economic safety benefits of €590 million (Table 2). In view of the growing funding limitations of safety budgets, it was then assumed that 80%, 60% or even 25% of the budget was available for the programme that required further optimisation. Based on these data, the newly developed model was then used. The study also carried out sensitivity analyses related to changes in crash severity levels and categorisation of measures.

### 4. Model results and discussion

Table 3 shows the budget allocation under road safety capital or maintenance works and its benefits under unconstrained (100%) budget availability together with the optimised results under certain assumed budget constraints. The results show that the balance between capital and maintenance work measure changes significantly. For instance, under-unconstrained budget
| Countermeasure                              | Life years | Category | Source of information                                                                 |
|--------------------------------------------|------------|----------|---------------------------------------------------------------------------------------|
| Pedestrian footpath                        | 10–20      | Capital  | [iRAP] International Road Assessment Programme, 2010                                   |
| Median barrier                             | 10–30      | Capital  | PIARC, 2021; [iRAP] International Road Assessment Programme, 2010; Grzyl et al., 2017 |
| Roadside barrier                           | 10–30      | Capital  | [iRAP] International Road Assessment Programme, 2010; Daniels & Papadimitriou, 2017; Daniels et al., 2019; Grzyl et al., 2017 |
| Pedestrian fencing                         | 10–20      | Capital  | [iRAP] International Road Assessment Programme, 2010                                   |
| Street lighting                            | 10–20      | Capital  | [iRAP] International Road Assessment Programme, 2010                                   |
| Traffic calming                            | 10–20      | Capital  | [iRAP] International Road Assessment Programme, 2010                                   |
| Bicycle lanes and tracks                   | 10–25      | Capital  | Elvik et al., 2009; [iRAP] International Road Assessment Programme, 2010               |
| Reconstruction and rehabilitation of roads | 25         | Capital  | Elvik et al., 2009                                                                    |
| Pedestrian crossing (signalised)           | 10–20      | Capital  | [iRAP] International Road Assessment Programme, 2010                                   |
| Sight distance (obstruction removal)       | 5–10       | Maintenance | [iRAP] International Road Assessment Programme, 2010                                 |
| Shoulder rumble strips                     | 1–5        | Maintenance | [iRAP] International Road Assessment Programme, 2010                                 |
| Refuge island                              | 5–10       | Maintenance | [iRAP] International Road Assessment Programme, 2010                                 |
| Protected turn lane (unsignalised 4 leg)   | 5–10       | Maintenance | [iRAP] International Road Assessment Programme, 2010                                 |
| Unsignalised crossing                      | 1–5        | Maintenance | [iRAP] International Road Assessment Programme, 2010                                 |
| Central hatching                           | 1–5        | Maintenance | [iRAP] International Road Assessment Programme, 2010                                 |
| Parking improvements                       | 5–10       | Maintenance | [iRAP] International Road Assessment Programme, 2010                                 |
| Centreline rumble strip/flexi-post         | 1–5        | Maintenance | [iRAP] International Road Assessment Programme, 2010                                 |

(Continued)
conditions, 74% and 26% of the total budget is required for capital and maintenance works, respectively. However, in a constrained budget scenario, the higher the budget constraint, the lower the budget allocation for capital works, and, as a consequence, the higher the budget allocation for maintenance works. For example, with 25% of the budget available, the model allocates approximately 40% and 60% to capital and maintenance work measures, respectively. As may be seen, the resulting economic benefits are higher with maintenance than capital work measures (Table 3).

The analysis shows that it is possible to identify a budget level below which maintenance countermeasures have a higher contribution to the overall benefits than the capital works in constrained budget scenarios. For example, the economic benefits in capital investment are higher than maintenance investment for funds above 60% of the budget (Figure 1).

Correspondingly, for funding availability below 60% of the budget, the economic benefits due to capital work measures diminish in comparison to maintenance works. This seems to be consistent with the budget allocation strategy for Greece in 2005 where short-term interventions had the largest share of the safe budgets (Yannis et al., 2008). Table 4 shows countermeasures prioritised during the optimisation process for different budget scenarios using the newly developed model. These were selected from the programme of countermeasures (Table 2) that are ideally identified to improve the safety condition of the road network during the road network safety management process. As may be observed, fewer countermeasures are selected and prioritised in comparison to those in Table 2 due to budget constraints usually faced by road safety improvement programmes. Furthermore, the results in Table 4 show that the number of countermeasures selected for implementation is dependent on the best mix that maximises economic benefits for any funds available. As an example, the model selected 22 countermeasures with 80% of the budget in comparison to 24 countermeasures for the 60% availability (Table 4). The model outputs seem to be reasonable for this case study, as revealed by the 16 countermeasures (Table 4) selected with 25% availability that produce the lowest cost-effectiveness ratio.

A non-life span approach showed that prioritisation changes in which there were more maintenance work measures selected than capital work for all budget scenarios in comparison to the life span approach resulted in Table 4. This clearly indicates the possibility of a biased selection in

Table 1. (Continued)

| Countermeasure                      | Life years | Category      | Source of information                           |
|------------------------------------|------------|---------------|-------------------------------------------------|
| Improve delineation                | 1–5        | Maintenance   | [iRAP] International Road Assessment Programme, 2010 |
| Protected turn lane (unsignalised 3 leg) | 5–10      | Maintenance   | [iRAP] International Road Assessment Programme, 2010 |
| Wide centreline                    | 5–10       | Maintenance   | [iRAP] International Road Assessment Programme, 2010 |
| Delineation and signing (intersection) | 1–5       | Maintenance   | [iRAP] International Road Assessment Programme, 2010 |
| Clear roadside hazards—driver side  | 5–10       | Maintenance   | [iRAP] International Road Assessment Programme, 2010 |
| Shoulder sealing passenger side (>1 m) | 5–10      | Maintenance   | [iRAP] International Road Assessment Programme, 2010 |
### Table 2. A programme of countermeasures in unconstrained budget

| S/N | Countermeasure                        | Category | Length/ sites | Crashes minimised | Economic benefits (€) | Costs(€) | BCR |
|-----|--------------------------------------|----------|---------------|-------------------|------------------------|----------|-----|
|     |                                      |          |               | Fatal  | Serious injury | Slight injury | PDO |       |               |               |          |
| 1   | Signalised crossing                   | C        | 1 sites       | 1.2    | 7.7           | 41.9          | 397.5 | 88,29,598 | 45,000       | 196        |
| 2   | Pedestrian fencing                   | C        | 27.20 km      | 1.0    | 6.9           | 37.7          | 357.8 | 79,46,638 | 1,79,606     | 44         |
| 3   | Street lighting (intersection)       | C        | 14 sites      | 2.4    | 16.1          | 88.0          | 834.8 | 1,85,42,156| 5,04,000     | 37         |
| 4   | Traffic calming                      | C        | 2.90 km       | 0.1    | 0.8           | 4.2           | 39.8  | 8,82,960  | 87,581       | 10         |
| 5   | Central median barrier (no duplication)| C        | 0.70 km       | 0.1    | 0.8           | 4.2           | 39.8  | 8,82,960  | 95,182       | 9          |
| 6   | Footpath provision driver side (>3 m from road) | C     | 25.40 km     | 3.3    | 21.5          | 117.4         | 1113.1| 2,47,22,875| 1,79,606     | 44         |
| 7   | Footpath provision passenger side (>3 m from road) | C     | 26.80 km     | 3.4    | 22.3          | 121.6         | 1152.9| 2,56,05,835| 30,85,368    | 8          |
| 8   | Footpath provision driver side (informal path >1 m) | C     | 4.70 km       | 0.1    | 0.8           | 4.2           | 39.8  | 8,82,960  | 1,14,747     | 8          |
| 9   | Footpath provision driver side (adjacent to road) | C     | 27.90 km     | 4.1    | 26.9          | 146.7         | 1391.4| 3,00,33,93 | 43,88,280    | 7          |
| 10  | Bicycle Lane (off-road)              | C        | 3.50 km       | 0.3    | 2.3           | 12.6          | 119.3 | 26,48,879 | 3,92,156     | 7          |
| 11  | Footpath provision passenger side (adjacent to road) | C     | 44.10 km     | 6.0    | 39.9          | 218.0         | 2067.2| 4,59,13,910| 69,39,120    | 7          |
| 12  | Roadside barriers—driver side         | C        | 206.20 km     | 23.1   | 152.9         | 834.1         | 7911.1| 17,57,09,003| 2,78,98,500 | 6          |
| 13  | Footpath provision passenger side (informal path >1 m) | C     | 5.80 km       | 0.1    | 0.8           | 4.2           | 39.8  | 8,82,960  | 1,41,451     | 6          |
| 14  | Central median barrier (1 + 1)        | C        | 34.80 km      | 4.8    | 31.5          | 171.9         | 1629.9| 3,62,01,352| 62,88,200    | 6          |
| 15  | Road surface rehabilitation           | C        | 0.80 km       | 0.0    | 0.3           | 1.7           | 15.9  | 3,53,184  | 70,435       | 5          |
| 16  | Improve curve delineation             | M        | 0.40 km       | 0.1    | 0.4           | 2.1           | 19.9  | 4,41,480  | 7,460        | 59         |
| 17  | Sight distance (obstruction removal)  | M        | 1.40 km       | 0.2    | 1.5           | 8.4           | 79.5  | 17,65,920 | 35,280       | 50         |
| 18  | Shoulder rumble strips                | M        | 199.30 km     | 9.8    | 64.5          | 352.1         | 3339.4| 7,41,68,624| 23,82,592    | 31         |
| 19  | Refuge Island                         | M        | 14 sites      | 1.6    | 10.8          | 58.7           | 556.6 | 1,23,61,437| 4,16,422     | 30         |
| 20  | Protected turn lane (unsignalised 4 leg) | M     | 3 sites       | 1.6    | 10.8          | 58.7           | 556.6 | 1,23,61,437| 5,35,399     | 23         |
| 21  | Unsignalised crossing                 | M        | 5 sites       | 0.5    | 3.1           | 16.8           | 159.0 | 35,31,839 | 2,17,665     | 16         |
| 22  | Central hatching                      | M        | 5.70 km       | 0.1    | 0.5           | 2.5            | 23.9  | 5,29,776  | 34,173       | 16         |

(Continued)
| S/N | Countermeasure                        | Category | Length/sites | Crashes minimised | Economic benefits (€) | Costs (€) | BCR |
|-----|--------------------------------------|----------|--------------|-------------------|----------------------|-----------|-----|
|     |                                      |          |              | Fatal | Serious injury | Slight injury | PDO     |      |
| 23  | Parking improvements                  | M        | 1.50 km      | 0.0   | 0.2           | 1.3          | 11.9    | 2,64,888 | 18,900 | 14  |
| 24  | Centreline rumble strip/flexi-post    | M        | 1.80 km      | 0.0   | 0.2           | 1.3          | 11.9    | 2,64,888 | 19,512 | 14  |
| 25  | Improve Delineation                   | M        | 45.70 km     | 1.5   | 10.0          | 54.5         | 516.8   | 1,16,78,478 | 8,47,446 | 14  |
| 26  | Protected turn lane (unsignalised 3 leg) | M       | 54 sites     | 8.6   | 56.9          | 310.2        | 2941.8  | 6,53,39,026 | 72,10,571 | 9   |
| 27  | Wide centreline                       | M        | 12.50 km     | 0.1   | 0.5           | 2.5          | 23.9    | 5,29,776  | 75,710  | 7   |
| 28  | Delineation and signing (intersection) | M        | 8 sites      | 0.1   | 0.4           | 2.1          | 19.9    | 4,41,480  | 88,582  | 5   |
| 29  | Clear roadside hazards—driver side    | M        | 0.10 km      | 0.0   | 0.1           | 0.4          | 4.0     | 88,296    | 20,000  | 4   |
| 30  | Shoulder sealing passenger side (>1 m) | M        | 71.50 km     | 3.4   | 22.3          | 121.6        | 1152.9  | 2,56,05,815 | 63,34,720 | 4   |
| Total|                                      |          |              | 78    | 513           | 2,801        | 26,568  | 59,00,82,044 | 7,13,95,898 |     |
The absence of life span categorisation. The major disadvantage with such a biased selection is the preclusion of certain measures that might improve the programme effectiveness most especially with limited funding of the safety budget. Arguably, with the life span-based approach, there is more guarantee and sustainability of the assumed economic safety benefits due to an improved mix between the two categories.

It seems therefore that this model may provide a solution to an earlier challenge identified by Elvik (2014) of obtaining the best mix between these two categories of countermeasures, more so in a financial constraint. Generally, maintenance-related measures in this case study are more cost-effective than capital work measures in all budget scenarios. Indeed, this life span-based approach improves the integration between the two different categories of measures. Sensitivity results show

| Category       | Budget (€)  | Economic benefits (€) | Budget (%) | Economic benefits (%) |
|----------------|-------------|-----------------------|------------|-----------------------|
| Capital        | 5,31,51,666 | 38,09,08,864          | 74%        | 65%                   |
| Maintenance    | 1,82,44,232 | 20,91,73,180          | 26%        | 35%                   |
| Total          | 7,13,95,898 | 59,00,82,044          |            | 29,960 (100%)         |

**Table 3. Budget optimisation results**

| Category       | Budget (€)  | Economic benefits (€) | Budget (%) | Economic benefits (%) |
|----------------|-------------|-----------------------|------------|-----------------------|
| Capital        | 4,62,15,112 | 34,02,92,712          | 81%        | 67%                   |
| Maintenance    | 1,08,97,774 | 17,11,17,612          | 19%        | 33%                   |
| Total          | 5,71,12,886 | 51,14,10,324          |            | 25,966 (87%)          |

**Constrained budget (optimisation results)**

| Category       | Budget (€)  | Economic benefits (€) | Budget (%) | Economic benefits (%) |
|----------------|-------------|-----------------------|------------|-----------------------|
| Capital        | 4,27,19,559 | 20,16,68,022          | 58%        | 49%                   |
| Maintenance    | 1,81,16,138 | 20,83,78,516          | 42%        | 51%                   |
| Total          | 4,28,35,697 | 41,00,46,538          |            | 20,819 (69%)          |

| Category       | Budget (€)  | Economic benefits (€) | Budget (%) | Economic benefits (%) |
|----------------|-------------|-----------------------|------------|-----------------------|
| Capital        | 69,89,212   | 8,77,66,206           | 39%        | 34%                   |
| Maintenance    | 1,08,39,362 | 17,04,99,540          | 61%        | 66%                   |
| Total          | 1,78,28,574 | 25,82,65,746          |            | 13,113 (44%)          |

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Table 4. Countermeasure selection for different budget scenarios

| S/N | Countermeasure                        | Category | Length/sites | Crashes minimised | Economic benefits (€) | Costs (€) | BCR |
|-----|---------------------------------------|----------|--------------|-------------------|-----------------------|-----------|-----|
|     |                                       |          |              | Fatal | Serious injury | Slight injury | PDO |          |          |          |          |          |
| 1   | Signalised crossing                   | C        | 1 sites      | 1.2   | 7.7          | 41.9           | 397.5 | 88,295,98 | 45,000   | 196      |          |          |
| 2   | Pedestrian fencing                    | C        | 27.20 km     | 1.0   | 6.9          | 37.7           | 357.8 | 79,466,388 | 1,79,605 | 44       |          |          |
| 3   | Street lighting (intersection)        | C        | 14 sites     | 2.4   | 16.1         | 88.0           | 834.8 | 1,85,42,156 | 5,04,000 | 37       |          |          |
| 4   | Traffic calming                       | C        | 2.90 km      | 0.1   | 0.8          | 4.2            | 39.8  | 8,82,960 | 87,581   | 10       |          |          |
| 5   | Central median barrier (no duplication) | C       | 0.70 km      | 0.1   | 0.8          | 4.2            | 39.8  | 8,82,960 | 95,182   | 9        |          |          |
| 6   | Footpath provision driver side (>3 m from road) | C     | 25.40 km     | 3.3   | 21.5         | 117.4          | 1113.1 | 2,47,22,875 | 43,88,280 | 7        |          |          |
| 7   | Footpath provision passenger side (>3 m from road) | C        | 26.80 km     | 3.4   | 22.3         | 121.6          | 1152.9 | 2,56,05,835 | 30,85,368 | 8        |          |          |
| 8   | Footpath provision driver side (adjacent to road) | C       | 27.90 km     | 4.1   | 26.9         | 146.7          | 1391.4 | 3,09,03,593 | 43,88,280 | 4        |          |          |
| 9   | Footpath provision passenger side (adjacent to road) | C       | 44.10 km     | 6.0   | 39.9         | 218.0          | 2067.2 | 4,59,13,910 | 69,39,120 | 7        |          |          |
| 10  | Roadside barriers—driver side         | C        | 206.20 km    | 23.1  | 152.9        | 834.1          | 7911.1 | 17,57,09,003 | 2,78,98,500 | 6        |          |          |
| 11  | Road surface rehabilitation           | C        | 0.80 km      | 0.0   | 0.3          | 1.7            | 5.9   | 3,53,184   | 70,435   | 5         |          |          |
| 12  | Improve curve delineation             | M        | 0.40 km      | 0.1   | 0.4          | 2.1            | 15.9  | 4,41,480   | 74,60     | 59        |          |          |
| 13  | Sight distance (obstruction removal)  | M        | 1.40 km      | 0.2   | 1.5          | 8.4            | 79.5  | 17,65,920 | 35,280   | 50        |          |          |
| 14  | Shoulder rumble strips                | M        | 199.30 km    | 9.8   | 64.5         | 352.1          | 3339.4 | 23,82,592 | 23,82,592 | 31        |          |          |
| 15  | Refuge Island                         | M        | 14 sites     | 1.6   | 10.8         | 58.7           | 556.6 | 1,23,61,437 | 41,64,220 | 30        |          |          |
| 16  | Protected turn lane (unsignalised 4 leg) | M      | 3 sites      | 1.6   | 10.8         | 58.7           | 556.6 | 1,23,61,437 | 5,53,399 | 23        |          |          |
| 17  | Unsignalised crossing                 | M        | 5 sites      | 0.5   | 3.1          | 16.8           | 159.0 | 35,31,839 | 2,17,465 | 16        |          |          |
| 18  | Central hatching                     | M        | 5.70 km      | 0.1   | 0.5          | 2.5            | 23.9  | 5,29,776   | 34,173   | 16        |          |          |
| 19  | Parking improvements                  | M        | 1.50 km      | 0.0   | 0.2          | 1.3            | 11.9  | 2,64,888   | 18,900   | 14        |          |          |
| 20  | Centreline rumble strip/flexi-post    | M        | 1.80 km      | 0.0   | 0.2          | 1.3            | 11.9  | 2,64,888   | 19,512   | 14        |          |          |
| 21  | Protected turn lane (unsignalised 3 leg) | M      | 5x sites     | 8.6   | 56.9         | 310.2          | 2941.8 | 6,53,39,026 | 72,10,571 | 9         |          |          |
| 22  | Clear roadside hazards—driver side    | M        | 0.10 km      | 0.0   | 0.1          | 0.4            | 4.0   | 88,296     | 20,000   | 4         |          |          |

Total: 67 × 445 × 2,428 × 23,026 × 51,14,10,324 × 5,71,12,886

(Continued)
Table 4. (Continued)

| Number | Description                                                                 | C | Sites | 1.2 | 7.7 | 41.9 | 397.5 | 88,29,598 | 45,000 | 196 |
|--------|------------------------------------------------------------------------------|----|-------|-----|-----|------|-------|-----------|--------|-----|
| 1      | Signalised crossing                                                         | C  | 1 sites | 1.2 | 7.7 | 41.9 | 397.5 | 88,29,598 | 45,000 | 196 |
| 2      | Pedestrian fencing                                                          | C  | 27.20 km | 1.0 | 6.9 | 37.7 | 357.8 | 79,46,638 | 1,79,606 | 44 |
| 3      | Street lighting (intersection)                                              | C  | 14 sites | 2.4 | 16.1 | 88.0 | 834.8 | 1,85,42,156 | 5,04,000 | 37 |
| 4      | Traffic calming                                                              | C  | 2.90 km | 0.1 | 0.8 | 4.2 | 39.8 | 8,82,960 | 87,581 | 10 |
| 5      | Central median barrier (no duplication)                                      | C  | 0.70 km | 0.1 | 0.8 | 4.2 | 39.8 | 8,82,960 | 95,182 | 9 |
| 6      | Footpath provision driver side (adjacent to road)                           | C  | 25.40 km | 3.3 | 21.5 | 117.4 | 1113.1 | 2,47,22,875 | 29,22,040 | 8 |
| 7      | Footpath provision passenger side (adjacent to road)                        | C  | 26.80 km | 3.4 | 22.3 | 121.6 | 1152.9 | 2,56,05,835 | 30,85,368 | 8 |
| 8      | Footpath provision driver side (informal path >1 m)                         | C  | 4.70 km | 0.1 | 0.8 | 4.2 | 39.8 | 8,82,960 | 1,14,747 | 8 |
| 9      | Footpath provision passenger side (informal path >1 m)                      | C  | 27.90 km | 4.1 | 26.9 | 146.7 | 1391.4 | 3,09,03,593 | 43,88,280 | 7 |
| 10     | Median bar (1 + 1)                                                          | C  | 44.10 km | 6.0 | 39.9 | 218.0 | 2067.2 | 4,59,13,910 | 69,39,120 | 7 |
| 11     | Road surface rehabilitation                                                 | C  | 0.80 km | 0.0 | 0.3 | 1.7 | 15.9 | 3,53,184 | 70,435 | 5 |
| 12     | Improve curve delineation                                                   | M  | 0.40 km | 0.1 | 0.4 | 2.1 | 19.9 | 4,41,480 | 7,460 | 59 |
| 13     | Sight distance (obstruction removal)                                        | M  | 1.40 km | 0.2 | 1.5 | 8.4 | 79.5 | 17,65,920 | 35,280 | 50 |
| 14     | Shoulder rumble strips                                                      | M  | 199.30 km | 9.8 | 64.5 | 352.1 | 3339.4 | 7,41,68,624 | 23,82,592 | 31 |
| 15     | Refuge Island                                                               | M  | 14 sites | 1.6 | 10.8 | 58.7 | 556.6 | 1,23,61,437 | 4,16,422 | 30 |
| 16     | Protected turn lane (unsignalised 4 leg)                                    | M  | 3 sites | 1.6 | 10.8 | 58.7 | 556.6 | 1,23,61,437 | 5,35,399 | 23 |
| 17     | Unsignalised crossing                                                       | M  | 5 sites | 0.5 | 3.1 | 16.8 | 159.0 | 35,31,839 | 2,17,465 | 16 |
| 18     | Central hatching                                                           | M  | 5.70 km | 0.1 | 0.5 | 2.5 | 23.9 | 5,29,776 | 34,173 | 16 |
| 19     | Parking improvements                                                        | M  | 1.50 km | 0.0 | 0.2 | 1.3 | 11.9 | 2,64,888 | 18,900 | 14 |
| 20     | Improve Delineation                                                        | M  | 45.70 km | 1.5 | 10.0 | 54.5 | 516.8 | 1,14,78,478 | 8,47,446 | 14 |
| 21     | Protected turn lane (unsignalised 3 leg)                                    | M  | 54 sites | 8.6 | 56.9 | 310.2 | 2941.8 | 6,53,39,026 | 72,10,571 | 9 |
| 22     | Wide centreline                                                            | M  | 12.50 km | 0.1 | 0.5 | 2.5 | 23.9 | 5,29,776 | 75,710 | 7 |
| 23     | Shoulder sealing passenger side (>1 m)                                      | M  | 71.50 km | 3.4 | 22.3 | 121.6 | 1152.9 | 2,56,05,835 | 63,34,720 | 4 |
| **Total** |                                                                                           |      | 54 | 357 | 1,947 | 18,462 | 41,00,46,538 | 4,28,35,697 |       |      |
Table 4. (Continued)

| C: 25% Budget availability |   |   |   |   |   |   |   |
|----------------------------|---|---|---|---|---|---|---|
| 1  | Signalised crossing   | C | 1 sites | 1.2 | 7.7 | 41.9 | 397.5 | 88,29,598 | 45,000 | 196 |
| 2  | Pedestrian fencing    | C | 27.20 km | 1.0 | 6.9 | 37.7 | 357.8 | 79,46,638 | 1,79,606 | 44  |
| 3  | Street lighting (intersection) | C | 14 sites | 2.4 | 16.1 | 88.0 | 834.8 | 1,85,42,156 | 5,04,000 | 37  |
| 4  | Traffic calming       | C | 2.90 km | 0.1 | 0.8 | 4.2 | 39.8 | 8,82,960 | 87,581 | 9   |
| 5  | Central median barrier (no duplication) | C | 0.70 km | 0.1 | 0.8 | 4.2 | 39.8 | 8,82,960 | 95,182 | 9   |
| 6  | Footpath provision driver side (>3 m from road) | C | 25.40 km | 3.3 | 21.5 | 117.4 | 1113.1 | 2,47,22,875 | 5,04,000 | 37 |
| 7  | Footpath provision passenger side (>3 m from road) | C | 26.80 km | 3.4 | 22.3 | 121.6 | 1152.9 | 2,56,05,835 | 30,85,368 | 8 |
| 8  | Road surface rehabilitation | C | 0.80 km | 0.1 | 0.4 | 2.1 | 19.9 | 3,53,184 | 70,435 | 9 |
| 9  | Improve curve delineation | M | 0.40 km | 0.1 | 0.4 | 2.1 | 19.9 | 4,41,480 | 7,460 | 9 |
| 10 | Sight distance (obstruction removal) | M | 1.40 km | 0.2 | 1.5 | 8.4 | 79.5 | 17,65,920 | 35,280 | 9 |
| 11 | Shoulder rumble strips | M | 199.30 km | 9.8 | 64.5 | 352.1 | 3339.4 | 7,41,68,624 | 23,82,592 | 9 |
| 12 | Refug Island           | M | 14 sites | 1.6 | 10.8 | 58.7 | 556.6 | 1,23,61,437 | 4,16,422 | 30 |
| 13 | Protected turn lane (unsignalised 4 leg) | M | 3 sites | 1.6 | 10.8 | 58.7 | 556.6 | 1,23,61,437 | 5,35,399 | 30 |
| 14 | Unsignalised crossing | M | 5 sites | 0.5 | 3.1 | 16.8 | 159.0 | 35,31,839 | 2,17,465 | 16 |
| 15 | Central hatching      | M | 5.70 km | 0.1 | 0.5 | 2.5 | 23.9 | 5,29,776 | 34,173 | 9 |
| 16 | Protected turn lane (unsignalised 3 leg) | M | 54 sites | 8.6 | 56.9 | 310.2 | 2941.8 | 6,53,39,026 | 72,10,571 | 9 |
| Total |                       |   |   |   |   |   |   |   | 34 | 225 | 1,226 | 11,628 | 25,82,65,746 | 1,78,28,574 |
that proportionate exclusion and inclusion of severity levels, such as slight injury and PDO crashes, do not affect prioritisation of countermeasures but result in commensurate changes in economic benefits.

5. Conclusion
This article presents an optimal budget allocation method addressing prioritisation of infrastructure countermeasures for road safety programmes under budget constraints by considering the life span of the countermeasures and their categorisation as capital or maintenance work. The conclusions that may be drawn, based on the case study presented, are as follows:

1. The importance of road safety-related maintenance programmes is high. The higher the budget constraints, the higher its importance.
2. The consideration of the life span of road safety countermeasures changes both their selection and prioritisation for subsequent implementation. It also increases the overall effectiveness of a road safety investment plan.
3. Using a formal optimisation method, it is possible to define a threshold level of investment above which the impact of capital countermeasures is superior to that of maintenance.
4. The economic benefits due to prioritised and selected countermeasures are commensurate with changes in the crash severity levels.
5. Proportionate exclusion of some severity levels, such as slight injury and PDO crashes, does not affect the prioritisation and selection of countermeasures.

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