PRAGMATIC SUSTAINABILITY ASSESSMENT OF 30-KM/H POLICY MEASURES: THE BRUSSELS' PENTAGON CASE

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Abstract

Increasing social, economic and ecological impact of motorised mobility requires an identification of sustainable mobility policies, as well as a clear evaluation of the impact of such measures. Still, there is a lack of practical oriented decision-supporting instruments to assist decision-makers in the sustainability assessment of mobility policies.

The present paper proposes a pragmatic assessment framework, including procedural Sustainability Assessment (SA) and Analytic Hierarchy Process (AHP) constituents, to determine the sustainability of traffic safety policies. The composite framework format provides decision-makers not only technical details on the assets and the limitations of the alternative policies, but offers procedures to reach and implement assessment decisions as well. The paper applies the pragmatic framework for the specific case of the present 30-km/h scenario in the Brussels' pentagon, of which the sustainability performance is compared to four general 30-km/h policy alternatives, i.e. 30-km/h speed regimes, speed reducing devices, (re-) constructing roads and junctions and (re-) constructing active mode infrastructure.

Results show that the sustainability performance of the Brussels' pentagon scenario can be enhanced by complementary active mode infrastructure and speed reducing devices, which benefit traffic safety, incite emission-free mobility and provide access to a larger quantity of travellers.

The proposed framework bridges the gap between policy impact assessment framework design and use, while specifying the assessment attributes according the basic dimensions of sustainable development. Both are beneficiary for decision-processes towards sustainability.

Keywords: 30-km/h zones, traffic safety infrastructure, sustainable safety, sustainability assessment, multi-criteria analysis

1. INTRODUCTION

1.1. Sustainable development and mobility

Despite the lack of a universal accepted definition on sustainable development (Steg and Gifford, 2005; Purnomo et al., 2005), three generic principles are commonly adhered in propagating sustainability (WCED, 1987): (1) meeting the needs of future generations, (2) acknowledging limitations of human activities and (3) incorporating social, economic and ecological attributes.

However, to determine progress towards thematic strategies like sustainable mobility, these generic principles require further operationalization. As such, the paper demarcates a working definition with an emphasis on sustainable mobility determinants and explicit attributes to examine actual unsustainable impacts: *"Mobility activities are determined by an interaction between mobility behaviour, infrastructure and land-use; and should be completed according socially acceptable (ensuring traffic safety, protecting health and life quality and enhancing inclusivity), economically feasible (accessible and efficient) and ecologically justified objectives (decreasing fuel consumption, greenhouse gas emissions and application materials), in order to serve the societal needs of today and the future"* (WCED, 1987; WBCSD, 2004; Macharis et al., 2010; Litman and Burwell, 2006; Gudmundsson and Höjer, 1996; Allaert, 2008; Richardson, 1999; Black, 2000).

1.2. Decision-processes towards sustainable mobility

There is no general consensus on how decision-processes contribute to the sustainability of mobility activities. Still, three overall policy categories towards sustainable mobility are commonly distinguished, i.e. physical policies, soft policies and knowledge policies (Santos et al., 2010). *Physical policies* refer to physical infrastructural elements like public transportation, walking and cycling facilities, being part of an integrated planning approach to curtail road construction and expansion. *Soft policies* comprise non-tangible strategies, i.e., car sharing and car clubs; teleworking and teleshopping; eco-driving; information and education; advertising and marketing; family life changes, which are directed on the modification of the mobility behaviour by sensitizing on the consequences of displacement choices. *Knowledge policies* sustain the former two categories by facilitating research on mobility technology and decision-process strategies. Undertaking research and development on the negative impact of mobility policies enhances the sustainability performance of mobility decision-processes.

This paper integrates sustainability attributes in the evaluation of mobility policies, in order to assist decision-makers in identifying policy options with minimal impact. To facilitate the evaluation, a theoretical framework is presented, aligning determinants and attributes for sustainable mobility (Figure

1). The focal determinants in the mobility decision-process, i.e. infrastructure, mobility behaviour and land-use are exemplified on each side of the triangle, and related to the generic sustainability objectives on the corners of the triangle. Between the generic objectives and the focal determinants, sub-objectives are illustrated on the sides of the main triangle, which are tiered from the generic sustainability objectives. The specific attributes to determine the impact of mobility options are listed in the sub-triangles. Social attributes address safety and liveability, while enhancing the inclusivity of vulnerable groups. Ecological attributes mitigate barrier effects of infrastructural landscape segregation and reduce impact on species and greenhouse gas emissions, while diminishing/recycling application materials during the policy implementation. Economic attributes achieve accessible destinations, retained from congestion for an efficient cost structure.

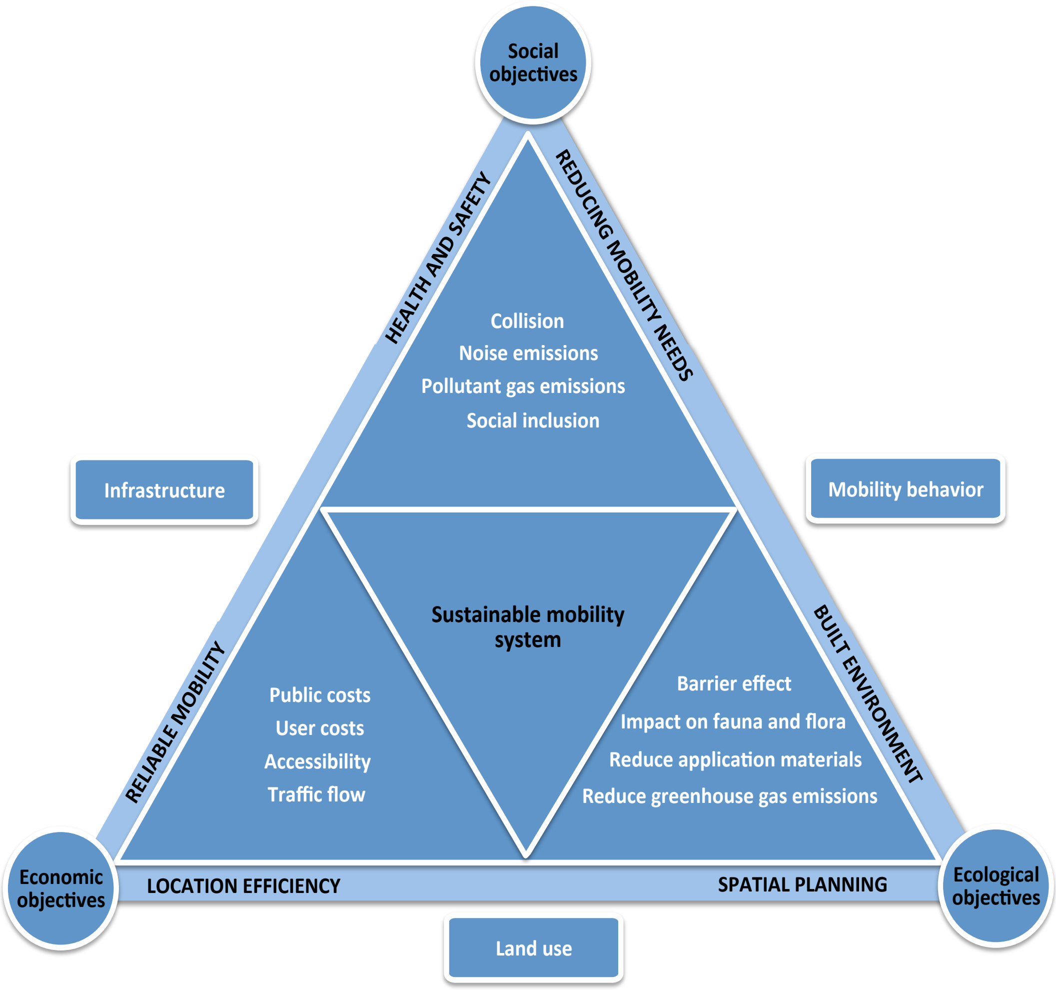

FIGURE 1- THEORETICAL FRAMEWORK FOR SUSTAINABLE URBAN MOBILITY.SOURCE: OWN SET UP

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1.3 Sustainability assessment of mobility policies

Within mobility policies, the assessment of infrastructural policies is particularly a topic of common interest (see for example Short and Kopp 2005; Masiero and Maggi 2012). The focus of infrastructure evaluations is predominantly an economic one, as infrastructural policies are generally considered in terms of investments and returns. Still, particular assessment studies also integrate social and ecological effects in the evaluation of mobility infrastructure. Thompolous et al. (2009) incorporate equity considerations in the evaluation of mobility infrastructure, while Lundberg et al. (2010) determine adverse ecological effects of regional transport infrastructure plans.

Studies on the sustainability assessment of infrastructural traffic safety policies are however scarce. Conform to the evaluation of general mobility infrastructure policies; the assessment of traffic safety infrastructure is principally directed on the explicit policy performance of reducing accidents (Koornstra et al., 1992; Elvik and Vaa, 2004; Kazaras et al., 2012).

Still, adverse social, economic and ecological effects need to be included in the assessment as well. Wei and Lovegrove (2012) determined the traffic safety effects of road structures in a broader framework of sustainable neighbourhoods. Their contribution showed that more sustainable land use, the built environment and the modal shift towards active mobility modes were key aspects in enhancing global road safety in sustainable communities.

The contributions of the present paper are twofold. The first one is the proposition of a pragmatic assessment framework, covering procedural and analytic assessment steps, to support the practical sustainability assessment of traffic safety policies. Section 2 examines possible assessment instruments and proposes a practical oriented approach. The second contribution is the application of the proposed assessment framework for the specific case of the Brussels pentagon (section 3), in order to compare the sustainability performance of an empirical 30-km/h case with the performance of general 30-km/h policy strategies. Section 4 discusses the contributions and the constraints of the proposed framework in enhancing sustainable decision-processes. Section 5 concludes the main findings.

2. ASSESSMENT FRAMEWORK

Policy impact assessment methodologies can be subdivided into procedural and analytical approaches. While procedural evaluation instruments provide the evaluation procedures for reaching and implementing decisions, analytical evaluation instruments provide decision-makers with the technical information, by modelling the actual effects in a quantitative, qualitative (Finnveden et al. 2003) or integrative way.

2.1. Procedural impact assessment instruments

Environmental Impact Assessment (EIA) is a procedural decision-supporting instrument to prevent ecological consequences of proposed policy actions and is described as one of the major policy innovations of the 20th century (Cashmore, 2004). EIA became the first regulatory auxiliary impact assessment instrument to address external effects of decision-making at the operational level (for projects) (Feldman, 1998). Five regulatory procedures integrate ecological considerations in the decision-making process: (1) identification of the relevant projects; (2) determination of the scope; (3) assembling the environmental impact statement (effects on the environment and possible mitigation measures); (4) consultation of relevant stakeholders; and (5) publishing information about the project and the decision of the assessment process (Jiricka and Pröbstl, 2009).
The Sustainability Assessment (SA) instrument covers assessment procedures to direct planning and decision-making towards sustainable development and must be distinguished from conventional EIA strategies, since it identifies social and economic effects as well (Hacking and Gurthrie, 2008; Ruddy and Hilty, 2008). In Belgium, the Federal Service for Public Planning and Sustainable Development (PODDO) determined four procedural steps to assess the sustainability of policies at the Ministerial level: (1) screening the requirements; (2) scoping the content, depth and method to cover all potential impacts; (3) assessing the actual social, economic and ecological impacts; and (4) formulating strategies to avoid or reduce the undesired impacts (Berger, 2007). In conclusion, the Belgian procedural SA steps correspond with the general EIA procedures in terms of preparation, actual impact assessment and follow-up.

The present paper recommends particularly specifying the link between the four generic procedural SA steps and the technical assessment in the third procedural step, in order to narrow the discrepancy between policy impact assessment framework design and usage (see McIntosh et al., 2008). Merging technical impact assessment procedure with preparation and follow-up procedures benefits the actual implementation of the instrument and transforms the sustainability impact statement (step 3) into real-world policy making (see Wrisberg et al., 2000).

To identify the actual policy impact, suitable analytical impact assessment tools will be overviewed in the next section.

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2.2. Analytic impact assessment instruments

Huppes and Ishikawa (2007) relate the choice for a particular analytical sustainability assessment tool to the scientific approach that performs the evaluation. Social Cost-Benefit Analyses (SCBA) are general applied analytical evaluation tools in the public sector, assessing the public net benefit of transport infrastructure investments. SCBA's provide a quantified resume of the advantages and disadvantages of feasible alternative policies, which are listed as quantified and monetised as possible on a cost-benefit balance (Wesemann, 2002). Nevertheless, extending the SCB evaluation scope from merely economic to social and ecological issues involves multiple assessment criteria which are, by nature, difficult to quantify and monetise (Damart and Roy, 2009). Since qualitative criteria cannot be measured in monetary terms, distinct measurement procedures are necessary to integrate these incommensurable criteria in the evaluation process. Moreover, in subjecting the policy strategies to multiple assessment criteria, the analytic evaluations instrument needs to deal with conflicting policy objectives (Munda, 2009). The multi-criteria analysis (MCA) serves as a very suitable instrument to evaluate public projects and policies in an interdisciplinary context, because it combines a wide range of assessment criteria, provides insights in the nature of the conflict and overcomes problems of monetarisation and incommensurability (Munda, 2009; Munda, 2004; Brouwer and van Ek, 2004). This paper aims to demonstrate the multi-criteria analysis as a complementary analytical impact assessment instrument, being part of the procedural sustainability impact assessment instrument (SA), to evaluate the sustainability of 30-km/h policies.

Multi Attribute Decision Making (MADM) approaches can be classified as (1) Outranking Methods, (2) Multi Attribute Utility/Value Methods and (3) Non-Classical MCA Approaches (Figueira et al., 2005; Herva and Roca, 2013). Outranking methods use the pairwise comparative social choice mechanism to let the alternative scenarios partially or completely outrank each another. Complete scenario outranking requires additional information on the preferences of the decision-maker and the trade-offs between the criteria, to address incomparability (Brans, 1996, Brans and Mareschal, 2005). Multi Attribute Utility Theory considers knowledge deficits on the consequence of particular choices by building a utility function, which aggregates all the individual objectives and the attitudes towards uncertainty and risk, to select the alternative with the highest expected utility given a set of attributes (Keeney, 1977; 1988). Multi Attribute Value Theory (MAVT) ranks the alternative scenarios by means of numerical eigenvectors, derived from pairwise compared priorities towards the best and worst alternatives on a relative scale (Saaty, 1990; Saaty and Hu, 1998). Uncertainties and risks in the choice between a pair of alternatives in the MAVT can be verified by applying the stochastic dominance technique (Stewart, 2005; Raharjo et al., 2011) or Monte-Carlo simulation (Durbrach and Stewart, 2012). Non-classical MCA approaches, such as the fuzzy set approach, permit the specification of the information available with the approximate level of detail, to address specific situations of complexity, internal/external uncertainty, imprecise knowledge and vague preferences (Figueira et al., 2005; Herva and Roca, 2013).

Any of the discussed classical approaches are applicable to identify the tangible impact of the 30-km/h policy measures. Still, the multi value Analytic Hierarchy Process (AHP) is particularly suitable to support the pragmatic sustainability assessment of mobility policies. The present paper applies the AHP to conduct the sustainability impact statement, since its user-friendliness is specifically advantageous to support decision-makers (Turcksin et al., 2011; Vidal et al., 2011; Dolan, 2008). Nevertheless, if the hierarchical decision tree includes too many alternatives and/or criteria, the pairwise comparison becomes impossibly tedious and impracticable. External uncertainty related to the consequences of the AHP pairwise comparison is not explicitly treated, because the identification of the attitudes of the decision-makers towards the risks included in the judgements is practically a complex task (Durbach and Stewart, 2012). Moreover, the AHP approach does not always provide a strictly correct ranking of the alternatives, but compensates (i.e. trade-offs) between criteria with good scores and criteria with bad scores. As such, detailed and often important information can be excluded (Macharis et al., 2004).

2.3. Proposed sustainability assessment framework

To perform the evaluation, the paper proposes a practical sustainability assessment instrument deducted from procedural and analytic impact assessment strategies, comprising 3 main methodological steps, of which the second step contains four sub-steps. The first methodological step scopes the decision problem (step 1) to clarify the overall objective, the content and the potential impacts of the scrutinised policies. Depending on the operational or strategic level of the residing decision problem, the overall objective is related to hierarchical long-term targets in crosscutting policy areas (Turnpenny, 2008). Next, information from backdrop decisions is gathered in consultation with the competent authorities to support the continuity of the decision-making process (Koornneef et al., 2008). Finally, possible policy effects are analysed by a thorough examination of relevant impact assessment guidelines (Labuschagne et al., 2005; Pinter et al., 2012).

The second step makes use of the AHP (step 2) to conduct the actual sustainability assessment. Hence, four analytical sub-steps must be carried out. To construct the hierarchy in the firs sub-step (2a), the decision problem is decomposed into constituents (partly retrieved from the scoping knowledge in the first step) and hierarchically structured in at least three levels (Turcksin et al., 2011; Dagdeviren, 2008). Next, the decision tree is proposed to the competent authorities, which weighed the criteria according to their relevance. To allocate the criteria weights, different methods are applicable, such as

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the point allocation mechanism (Geldermann et al., 2009; Lebeau, 2010), the direct ranking and rating mechanism (Jalilova et al., 2012; Yeh et al., 1999) and the pairwise comparison mechanism (Saaty and Hu, 1998; Saaty, 1977).

As the weighted criteria of the decision tree are still too abstract to determine the impact on the alternative policies, the second sub-step selects qualitative or quantitative indicators (2b) in order to pinpoint the tangible impacts. As a result of this substantiation, the alternatives can be lexicographically differentiated according the criteria, to the support priority setting in the next step.

To determine the most sustainable alternatives, the third sub-step uses the pairwise comparison mechanism (Saaty, 1977) to set priorities between the optional policies (2c). This technique forces the assessor to choose between the best and the worst alternative in relation to each assessment criterion. The preference for a certain alternative is expressed on a 1-9 ratio scale (Saaty, 2008) and subsequently inserted as scalar in a comparison matrix, per (sub-) criterion (see table 1). Next, the eigenvalues are computed for each alternative based on the n^{th} root from the product of the scalars, divided by the sum of each n^{th} root from the product of the scalars for each alternative. The sum of each alternative's eigenvalue per N vectors is additionally equal to 1. The eigenvalues for each alternative per sub-criterion are multiplied with the weight of each sub-criterion and additively aggregated to determine the overall eigenvalues for each alternative per criterion. The overall eigenvalues for each alternative per criterion are subsequently multiplied with the weight of each criterion and additively aggregated to determine the final values of the alternatives (Ramanathan, 2006).

To consider the degree of random judgements, the fourth sub-step verifies the consistency ratio (2d), according to the transitivity rule: if A < B and B < C, then A < C. The difference between the maximum eigenvalue of a comparison matrix and the dimensions of the matrix can give a first impression of the inconsistency degree. The actual consistency ratios are however determined by dividing the consistency indices by the random indices computed by Saaty (1988). The consistency ratio of each matrix may not exceed 10% to be considered as reliable.

TABLE 1. AHP PAIRWISE COMPARISON MATRIX TO DETERMINE EIGENVECTORS PER SUB-CRITERION. SOURCE: SAATY (2008)

C	a_1	…	a_j	…	a_n
a_1	1				
…		1			
a_i			$P[a_i,a_j]$		
…				1	
a_n					1

Finally, accompanying implementation measures (step 3) are proposed in the last methodological step, to avoid or reduce the impact of the scrutinised policies. As the analytic evaluation disclosed valuable information on the merits and drawbacks of the individual policies, implementation pathways are identified to transmit this valuable information into policy recommendations in order to avoid future policy impact (Macharis et al., 2010). A common deficit in eventual policy implementations is the gap between the impact studies and the actual implementation of the policy measures, which is often carried out by several different governmental departments. As such, this last methodological step pays particularly attention to the implementation process. Clear communication between the study departments, the public executive departments and the subcontractors benefit the actual mitigation of the undesired policy impacts.

3. APPLICATION OF THE PROPOSED METHODOLOGY

3.1. Scoping decision problem (step 1)

As the sustainability of mobility activities is influenced by a variety of interacting constituents, the examination of specific mobility sub-domains is imperative to pave to way to an inherent sustainable mobility system. The Brussels City Council introduced a 30-km/h zone of 4.6 km^2 over the entire central pentagon in September 2010, which was advocated as enhancing the traffic safety and -liveability in the central area. Still, no examination of optional 30-km/h strategies and their possible adverse effects substantiated the statements on the merits of the applied 30-km/h measures. The overall objective of this assessment is to elucidate the suppositions on the merits of 30-km/h policies.

To frame the operational scope of the decision problem (Brussels City municipal project level), the assessment objective is related to sustainable mobility targets on strategic level. The formal link with this strategic reference framework facilitates the actual tiering of mitigating policy objectives to lower levels, which often fail to ooze out (Weaver and Jordan, 2008). The Federal Sustainable Development Assessment Procedures (PODDO, 2013) on the Federal level and the Brussels Environmental Institute's Mobility Recommendation Plan (BIM, 2007) on the Regional level provide the strategic targets to conduct the operational traffic safety sustainability assessment. Two formal consultations with the City of Brussels' Department for Urbanism and Architecture effected in the political support of the competent authority and provided valuable backdrop information on preceding 30-km strategies in the central pentagon. Next, potential impacts of mobility- and traffic safety policies were scrutinised by reviewing the European Impact Assessment Guidelines (EC, 2009).

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3.2. Building the hierarchy for the sustainable 30-km/h decision problem (step 2a)

Four physical policy measures[1] are generally enforced to realise 30-km/h zones (Elvik and Vaa, 2004). The performance of these general policies is mutually compared to the performance of the empirical 30-km/h scenario in the Brussels pentagon, principally based on a combination of the first two general policies.

- 30-km/h speed regimes restrict vehicle speed to a limit of 30-km/h on residential and municipal access roads, to reduce vehicle braking distance and accident severity.
- Speed reducing devices (speed inhibitors, speed humps, rumble strips, etc.) mitigate vehicle speed by making certain speed levels inconvenient or even damaging for vehicles. As such, the street level is raised, roads are narrowed or noise producing application materials are implemented.
- (Re-) Constructing roads and junctions (speed tables, road alignment, transverse profile, mutual road structure, etc.) rehabilitate and/or resurfacing the existing road in combination with an altered alignment and a transformed transvers profile (cross-section) to control vehicle speed.
- (Re-) Constructing active modes infrastructure (cycle lanes, sidewalks, pedestrian crossings, etc.) separate pedestrian and bicycle traffic in time (traffic lights) or in space (cycle lanes) from vehicle traffic. By focussing on good visibility conditions and active road user priority, vehicle speed is mitigated (Elvik and Vaa, 2004).
- The Brussels pentagon scenario consists of a 30-km/h speed regime (traffic signs, repetitive traffic markings on the entrance roads and informative display-speed-cameras) and a limited amount of speed reducing devices (speed inhibitors).

The four policy categories and the empirical combined scenario constitute the bottom level in the hierarchy (Figure 2). They serve as alternative policy strategies to address the overall objective of the assessment, i.e., sustainable 30 km/h zones (top of hierarchy). Each alternative will be individually subjected to specific sub-criteria as constituents of sustainability criteria at the 2 intermediate levels.

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[1] See general policy categories in section 3.1.2
[2] See part 4.2 for a discussion on the robustness of the ranking results

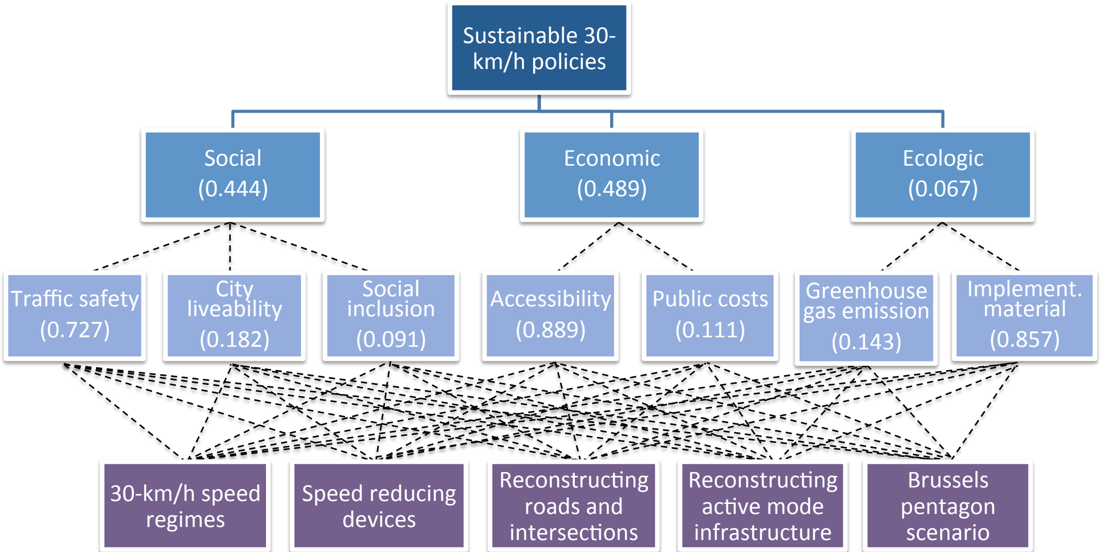

FIGURE 2- HIERARCHICAL WEIGHED DECISION TREE.
Source: Own set up

The selected assessment criteria originate from the theoretical framework for sustainable mobility. While the main criteria consist of the basic sustainability dimensions, the sub-criteria are derived from the framework's specific assessment attributes (Figure 1), competed by policy objectives of the Federal Sustainable Development Assessment Procedures (PODDO, 2013) and the Brussels Environmental Institute's Mobility Recommendation Plan (BIM, 2007). The latter policy plans were pinpointed as the strategic reference framework for the 30-km/h projects in the first methodological step. The City of Brussels' competent Department for Urbanism and Architecture consequently weighed the individual assessment criteria by means of the pairwise comparison mechanism. The significance of the selected (sub-) criteria and the ascertained weights is discussed below.

The *social criterion* determines the performance of the 30-km/h alternatives with respect to human wellbeing and societal equity, being weighed as second preferable criterion (0.444) by the decision-makers. The *traffic safety* sub-criterion addresses the degree in which collision (damage accidents, injury accidents and fatal accidents) can be precluded. The traffic safety performance is highly rated by the Department of Urbanism and Architecture with a weight of 0.727 in relation to the residual social sub-criteria. The alternative's ability to reduce pollutant gas and noise emissions is conjointly considered by the *city liveability* sub-criterion, weighed as second most preferable social sub-criterion (0.182) by the decision-makers. Travel possibilities for vulnerable road users (youngsters, elderly, people with a reduced mobility and people with less financial means) are accounted for by the *social inclusion* sub-criterion, which obtained the lowest weight in the social criteria group (0.091).

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The alternatives their contribution to general welfare and related implementation expenses are examined by the *economic criterion*, being slightly preferred over an almost equally well performing social criterion (0.489). 30-km/h policies should provide access to large quantities of different types of travellers *(accessibility)*, based on particular financial resources *(public costs).* The competent decision-makers value the economic accessibility sub-criterion over the public cost sub-criterion with allocated weights of 0.889 and 0.111 respectively.

The *ecological criterion* identifies the merits with respect to ecological damage and deprivation, for a weight of 0.067 in relation to the other parent assessment criteria. The ecological criterion acknowledges the reduction of *greenhouse gas emissions* and perspectives to re-use and recycle manufacturing materials *(reducing application materials),* as sibling child sub-criteria, weighed 0.143 and 0.857 respectively in the benefit of reducing application material.

3.3. Impact assessment literature study to select indicators (step 2b)

To conduct the pairwise comparison, the criteria require operationalization, allowing the assessor to set priorities. This section selects indicators from the literature, to determine the tangible impact of a particular criterion on the individual alternatives. The preference for one alternative over the other substantiates the evaluation as a result of this review. Table 2 provides an overview of the selected indicators, the units per sub-criterion and the scientific sources. The decision matrix (table 3) provides background on the degree (high, medium or low) in which the alternative scenarios comply with the criteria, relying on the indicators.

The subsequent subsections provide a literature review per sub-criterion on the impact of the 30-km/h alternatives. Based on the defined indicators, the proposed alternatives are lexicographically ranked according their contribution to each criterion, at the end of each subsection. This ranking is subsequently transmitted to Saaty's (2008) 9-point ratio scale, of which the scale scalars are intercalated in a comparison matrix (see section 2.3, table 1) to calculate the eigenvalues. These comparison matrices, derived from the lexicographical ranking, are shown in Tables 4-10.

TABLE 2 - INDICATOR OVERVIEW FOR THE PAIRWISE COMPARISON. SOURCE: OWN SET UP

Category	*Criteria*	*Indicator*	*Unit of measurement*
Social	*Traffic safety*	*Accident numbers*[1,2,3]	*# Fatal and injury accidents*
	City liveability	*Pollutant gas and noise emissions*[4,5,6,2,3]	*# NO_x, CO, PM_{10}, $PM_{2,5}$, SO_2; # > 55 dB(A)*
	Social inclusion	*Societal groups with access to transport modes*[7,8]	*% Car ownership, % bike ownership, % of domestic budget assigned to mobility*

Economic	*Accessibility*	*Travel time per mode[9]*	*# Minutes*
	Public cost	*Implementation and operational costs[1]*	*# Euros*
Ecological	*Greenhouse gas emissions*	*CO_2 equivalent (emitted by vehicles and in road construction sector)[4, 10, 11, 12]*	*# Tonnes*
	Implementation materials	*Recycled and reused materials[13]*	*# Tonnes*

Source: Elvik and Vaa 2004[1]; Dijkstra 2000[2]; Wei and Lovergrove 2012[3]; El-Shawarby et al. 2005[4]; Jayaratne et al. 2009[5]; Behzad et al. 2007[6];Stanley andVella-Brodrick 2009[7], Stanley and Lucas 2008[8]; RodrigezandJoo 2004[9]; Carslaw et al. 2010[10]; AhnandRakha 2009[11]; Huang et al. 2009[12]; Chowdhury et al. 2010[13].

TABLE 3 - DECISION MATRIX ON HOW 30-KM/H ALTERNATIVES COMPLY WITH SUSTAINABILITY CRITERIA.

	Social criteria			***Economic criteria***		***Ecological criteria***	
	Traffic safety	*City liveabil.*	*Social inclusion*	*Accessibility*	*Public costs*	*Greenhouse gas*	*Application material*
30-km/h speed regimes	*L*	*M*	*L*	*L*	*H*	*M*	*H*
Speed inhibitors	*H*	*L*	*L*	*L*	*M*	*L*	*M*
Recon. roads and intersections	*M*	*L*	*M*	*M*	*L*	*L*	*L*
Recon. active mode infrastruct.	*L*	*H*	*H*	*H*	*L*	*H*	*L*
Brussels Pentagon scenario	*M*	*M*	*L*	*L*	*M*	*M*	*M*

L = Low, M = Medium, H = High.

Source: Own set up

3.3.1. Traffic safety

Speed intensity has a significant influence on the severity of accidents, i.e., fatal accidents or injury accidents. Both categories are classified here as all injury accidents, to determine the traffic safety effects of the 30-km/h alternatives.

Reducing the speed limit from 50- to 30-km/h reduces all injury accidents by approximately 13% (Elvik and Vaa, 2004). Speed reducing devices (horizontal and vertical) compel the appropriate speed more effectively. It is estimated that the implementation of speed inhibitors in 30-km/h zones reduces the amount of all injury accidents by about 26% (Dijkstra, 2000).

Reconstructing the road layout seems less effective in urban areas, as it only decreases all injury accidents by about 5-10% (Elvik and Vaa, 2004). Special attention should be given to the design of the mutual road structure (relation between roads and intersections), which can have a significant influence on traffic safety. The "limited access road structure" and "organic road structure" are found to be safer

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than the "grid road structure", since they reduce the amount of intersections (Dijkstra, 2000; Wei and Lovegrove, 2012).

Devoting more space to active mobility modes (walking, cycling, skateboarding, scooting, rollerblading) also contributes to the reduction of vehicle speed. It is assumed that increasing walking and roll activities enhances the awareness of vehicle drivers, which reduces the accident rate involving active road users. Other studies conclude, however, that more cycle and pedestrian lanes do not reduce the amount of accidents (Elvik and Vaa, 2004), since they amplify the physical walking and roll activities, which in turn increases the collision exposure level among active road users. Wegman et al. (2012) conclude in an extensive review on cycling and road safety that if the number of cyclists increases, the number of fatalities may increase, but will not necessarily do so. This evaluation considers the traffic safety effects of active mode infrastructure therefore as inadequate.

The current 30-km/h scenario in the Brussels' pentagon has not benefited the traffic safety situation so far. Between September 2009 and September 2010, the year before the implementation of 30-km/h zone, 424 accidents occurred involving 755 road users (1 fatality, 27 heavy injured and 510 slightly injured). Between September 2010 and September 2011, the year ex post the 30-km/h zone implementation, 889 people were involved in 498 accidents (1 fatality, 17 heavy injured and 564 slightly injured) (Federal Police, 2012). These figures demonstrate an increase in the amount of accidents and the involved road users in the central pentagon.

The effectiveness of the current 30-km/h scenario may also be indicated by the average vehicle speed in the Brussels pentagon. Ten display-speed-cameras captured the velocity of 1,672,076 vehicles between March and October 2011. The overall mean V85 speed (15% highest offences not included) was found to be 36.76-km/h (DUA, 2012b). The prevalent 30-km/h regime was especially violated in Rue de la Loi (average 48-km/h), Rue de la Senne (average 43-km/h) and Rue du Grand-Serment (average 42.5-km/h). Three streets with no credible 30-km/h road lay-out.

TABLE 4. COMPARISON MATRIX AND EIGENVECTORS FOR TRAFFIC SAFETY SUB-CRITERION. SOURCE: OWN SET UP

	30-km/h regime	*Speed inhibitor*	*Recon. roads / inters.*	*Recon. active mode infr.*	*Brussels pent. scenario*	*Eigenvectors*
30-km/ regime	*1*	*-4*	*-3*	*1*	*-2*	*0.086*
Speed inhibitors	*1/-4*	*1*	*3*	*4*	*2*	*0.423*
Roads / intersect.	*1/-3*	*1/3*	*1*	*3*	*2*	*0.240*
Active mode infr.	*1*	*1/4*	*1/3*	*1*	*-2*	*0.086*
Brussels scenario	*1/-2*	*1/2*	*1/2*	*1/-2*	*1*	*0.165*

Consistency ratio: 0.02

Based on these indicators, the alternatives are lexicographically ranked according their traffic safety performance: 30-km/h speed regimes < active mode infrastructure < Brussels pentagon scenario <

reconstructing roads and intersections < speed inhibitors. This ranking is related to the relative 9-point ratio scale to compute the eigenvalues (table 4).

3.3.2. City liveability

Vehicle exhaust gas emissions and noise emissions affect urban liveability. Vehicle speed is strongly related to the combustion of fuel and exhaust gas emissions. The optimal fuel combustion point of a vehicle is reached between 60- and 70-km/h (El-Shawarby et al., 2005). Driving at 30-km/h increases the amount of emitted pollutants, i.e., NO_x, CO, PM_{10}, $PM_{2,5}$, SO_2 and O_3 in the enforced area over the same distance. However, lower speed regimes reduce decibel emissions from tires and motors.

Next to speed intensity, pollutant emissions strongly depend on driving practices (Jayaratne et al., 2009). The accelerations and decelerations, caused by the speed reducing devices, increase the emission of pollutants. In general, speed inhibitors, cause less vehicle noise emissions. Particular implementations, like rumble strips, however, emit more decibels (Behzad et al., 2007).

If reconstructed roads and intersections hinder speed perseverance, more pollutant gas will be emitted. The amount of intersections (potential exchange points for vehicles) between the roads determines the distribution of the vehicles along the network (Dijkstra, 2000). "Limited access" and "organic" road structures contain fewer intersections than "grid road structures". Particular roads in these restricted road structures will be exposed to more gas and noise emissions from vehicle detouring (Wei and Lovegrove, 2012). Next to the vehicle emissions, pollutant exhaust gases and noise emitted during the road construction process must be considered.

The implementation of walking and cycling infrastructure fosters more space for non-motorised road users (Hankey et al., 2012), sustaining general liveability and feelings of traffic safety (Cole et al., 2010; Wegman et al., 2012). Active mode infrastructure enhances emission free mobility (Woodcock et al., 2007). Noise and pollutant gas are only emitted during the infrastructure construction phase.

For the pollutant gas emitted in Brussels, data collected by the Brussels Environmental Institute's (BIM, 2012a) telemetric measurement device (B004) was examined. This is the only measurement device in the central pentagon and is merely configured for nitric oxides (NO_x), carbon monoxide (CO) and ozone (O_3) concentrations. An analysis of the annual average NO_x, CO and O_3 immission levels during 2009, 2010 and 2011 disclosed, in particular, problematic ambient air concentrations for nitric dioxide (respectively 42 $\mu g/m^3$, 43 $\mu g/m^3$ and 40 $\mu g/m^3$). These levels exceed (or are equal to) the average NO_2 limit (40 $\mu g/m^3$) to be respected from 1 January 2010 onwards (2008/50/EC directive). Average

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NO, CO and O_3 concentrations are not significant. Vehicle speed at 30-km/h increases all pollutant gas emissions and is particularly adverse for the NO_2 immission concentration in the central pentagon.
The annual average noise level in the central pentagon is generally between <45 and 55 dB(A) during the 24 hours of the day (BIM, 2006), which is generally categorised as very quiet and quiet. Vehicle speed at 30-km/h generally results in less vehicle noise emissions, which is in contrary to the pollutant gas emissions beneficiary for the liveability in the Brussels pentagon area.

TABLE 5. COMPARISON MATRIX AND EIGENVECTORS FOR CITY LIVEABILITY SUB-CRITERION. SOURCE: OWN SET UP

	30-km/h regime	Speed inhibitor	Recon. roads / inters.	Recon. active mode infr.	Brussels pent. scenario	Eigenvectors
30-km/ regime	1	4	3	-3	-2	0.233
Speed inhibitors	1/4	1	-2	-7	-4	0.051
Roads / intersect.	1/3	1/-2	1	-4	-2	0.092
Active mode infr.	1/-3	1/-7	1/-4	1	3	0.464
Brussels scenario	1/-2	1/-4	1/-2	1/3	1	0.161

Consistency ratio: 0.02

As a result of the general and empirical data, the alternatives are lexicographically ranked according their contribution to city liveability: speed inhibitors < reconstructing roads and intersections < Brussels pentagon scenario < restricted speed regime < active mode infrastructure. Based on this ranking, relative ratio scores are derived from a 9-point scale, to complete the comparison matrix, which enables the calculation of the eigenvalues per alternatives (table 5).

3.3.3. Social inclusion

Vulnerable groups (elderly, youngsters, people with less financial means, and people with reduced physical mobility) can be excluded from mobility means and systems, which impedes their access to basic needs and social capital (Stanley and Vella-Brodrick, 2009; Stanley and Lucas, 2008). This assessment criterion determines the extent in which the policy alternatives include vulnerable groups in the provision of their traffic safety objectives.
30-km/h speed regimes are directly related to motorised transport and feature no specific perspectives to include the safe displacement of vulnerable groups particularly.
Speed reducing devices focus principally on impeding vehicle speed as well, but offer the possibility to integrate pedestrian crossings or cycle lanes in the speed-inhibiting infrastructure.
Redesigning the layout of roads and intersections can offer even more benefits to vulnerable road users. The new road design can harbour public transport facilities and safe infrastructure for active mobility modes.
More cycle and pedestrian infrastructure supports the immediate mobility of vulnerable groups, who do not possess a vehicle or the ability to handle the task of driving.

No data for the case of Brussels has been found on the inclusion of vulnerable road users. Still, as the 30-km/h speed regime is completed with a minimal amount of speed inhibitors, the performance is pinpointed superior than the individual alternatives respectively.

The lexical order of the alternatives towards the inclusion of vulnerable groups is consequently determined: 30-km/h speed regimes < Brussels pentagon scenario < speed inhibitors < reconstructing roads and intersections < active mode infrastructure. Table 6 illustrates the comparison matrix, including the scalars deduced from the lexical order in relation to Saaty's (2008) 9-point ratio scale.

TABLE 6. COMPARISON MATRIX AND EIGENVECTORS FOR SOCIAL INCLUSION SUB-CRITERION. SOURCE: OWN SET UP

	30-km/h regime	*Speed inhibitor*	*Recon. roads / inters.*	*Recon. active mode infr.*	*Brussels pent. scenario*	*Eigenvectors*
30-km/ regime	*1*	*-3*	*-4*	*-7*	*-2*	*0.055*
Speed inhibitors	*1/-3*	*1*	*-2*	*-4*	*2*	*0.146*
Roads / intersect.	*1/-4*	*1/-2*	*1*	*-2*	*3*	*0.251*
Active mode infr.	*1/-7*	*1/-4*	*1/-2*	*1*	*4*	*0.454*
Brussels scenario	*1/-2*	*1/2*	*1/3*	*1/4*	*1*	*0.094*

Consistency ratio: 0.01

3.3.4. Accessibility

The quality of a mobility system determines the extent in which people obtain access to labour, residence, goods and services. This criterion assesses how the policy alternatives can optimise safe accessibility.

Driving under a restricted speed regime of 30-km/h can cause subjective impressions of delay among particular drivers. An increased speed from 30- to 50-km/h, over 5 km, gains the driver a theoretical time saving of four minutes. Since 30-km/h zones ideally harbour only origin and destination traffic, an average trip should not exceed 5 km. Hence, the alternative 30-km/h policy strategies exert theoretically a limited influence on the accessibility of vehicles.

The extent to which mobility systems provide access to goods, services and activities is traditionally considered from a motorised road user's point of view, as physical movements are commonly measured in terms of travel speed, vehicle loss hours and level of service ratings (Litman, 2012). On the other hand, accessibility-based approaches consider the option values of mobility modes in a broader context of optimal opportunities, such as efficient spatial planning to minimize travel distance, area walkability/cyclability, transit service frequency and telecommunication technologies as substitutes for travel (Ratner and Goets, 2013; Litman, 2012). A crucial aspect in mobility-based approaches is to determine how a built environment in favour of active mobility can contribute to the urban mobility problem. The attractiveness of cycling, walking and rolling activities is strongly related to the built environment (Rodrigez and Joo, 2004). Hence, the accessibility criterion is considered from an

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accessibility-based perspective, determining how the 30-km/h alternatives contribute to a built environment in favour of active and pubic transport mobility.

Speed reducing devices optimise the accessibility of active road users and public transport users more effectively than 30-km/h speed regimes. Still, assigning more public space to active/public transport road users by adapting roads, altering junctions and constructing walking and cycling infrastructure advances the safe accessibility of the active road user inherently.

No data on the accessibility of active road users for the Brussels pentagon has been found. As the Brussels scenario merely completes informative 30-km/h measures with limited compelling 30-km/h measures, humble accessibility enhancements for active road users are provided.

The lexicographical order of the policies towards the accessibility performance consists of: 30-km/h speed regimes < Brussels pentagon scenario < speed inhibitors < reconstructing roads and intersections < active mode infrastructure. The scaled scalars derived from the order are exemplified in table 7.

TABLE 7. COMPARISON MATRIX AND EIGENVECTORS FOR ACCESSIBILITY SUB-CRITERION. SOURCE: OWN SET UP

	30-km/h regime	*Speed inhibitor*	*Recon. roads / inters.*	*Recon. active mode infr.*	*Brussels pent. scenario*	*Eigenvectors*
30-km/ regime	*1*	*-4*	*-5*	*-8*	*-3*	*0.043*
Speed inhibitors	*1/-4*	*1*	*-2*	*-4*	*2*	*0.147*
Roads / intersect.	*1/-5*	*1/-2*	*1*	*-2*	*3*	*0.251*
Active mode infr.	*1/-8*	*1/-4*	*1/-2*	*1*	*5*	*0.466*
Brussels scenario	*1/-3*	*1/2*	*1/3*	*1/5*	*1*	*0.093*

Consistency ratio: 0.02

3.3.5 Public costs

Mobility related greenhouse gas (GHG) emissions are directly related to the fuel combustion process. The amount of emitted GHGs is determined by vehicle speed, driving style, road layout properties, engine performance and road construction techniques.

30-km/h speed regimes have a significant impact on fuel consumption and GHG emissions. Vehicles consume more fuel per km at low speed, since the optimal fuel consumption level is situated between 60- and 70-km/h (El-Shawarby et al., 2005). Petrol vehicles emit 237.1 g CO_2 per km, while diesel vehicles emit 195.0 g CO_2 per km under a 30-km/h speed regime. The optimal GHG emission level is reached at about 95-km/h, where each type of engine emits 156.9 g CO_2 and 138.5 g CO_2 per km respectively (Carslaw et al., 2010).

Speed reducing devices, sinuous road layout and grade-separated intersections impede the speed persistence of vehicles. The obtained moderated and inhibited vehicle speeds entail a higher level of fuel consumption and increasing GHG emissions (Ahn and Rakha, 2009). Active mode infrastructure, on the other hand, allows for emission free mobility.

One important and often ignored aspect in considering mobility related GHGs are the gasses emitted during the road infrastructure construction phase. Natural gas and oil provide energy in construction plants (production of bitumen, emulsion, asphalt etc.), in construction vehicle engines (pavers, rollers, etc.) and in transport vehicle engines (trucks, locomotives, etc.). The European Environmental Agency's EMEP/CORINAIR Emission Inventory Guidebook specifies GHG emission limits for transport related industrial activities, i.e., cement/asphalt production, road transport activities and other mobile sources and machinery activities (Huang et al., 2009). Innovative bitumen applications, generated at lower production temperatures, and construction/transportation vehicles with more efficient engines can reduce the road infrastructure related GHG emissions.

Within the Brussels Capital Region, the road transport sector is responsible for about 1/5 of the total emitted GHGs. These road transport related GHG emissions remained stable between 1990 en 2008, with an average annual share of 722.9 tonne CO_2 equivalent (BIM, 2012b). Vehicle speed at 30-km/h in the central pentagon can amplify the road transport related GHG emissions within the Brussels Capital Region. However, no exact figures were found.

As a result of the potential GHG's emitted during the mobility activities and during the construction phase, the alternatives are lexically ranked: reconstructing roads and intersections < speed inhibitors < Brussels pentagon scenario < 30-km/h speed regimes < active mode infrastructure. Table 9 translates the ranking into a comparison matrix to compute the eigenvalues.

TABLE 8. COMPARISON MATRIX AND EIGENVECTORS FOR PUBLIC COST SUB-CRITERION. SOURCE: OWN SET UP

	30-km/h regime	*Speed inhibitor*	*Recon. roads / inters.*	*Recon. active mode infr.*	*Brussels pent. scenario*	*Eigenvectors*
30-km/ regime	*1*	*3*	*4*	*5*	*2*	*0.417*
Speed inhibitors	*1/3*	*1*	*2*	*3*	*-2*	*0.163*
Roads / intersect.	*1/4*	*1/2*	*1*	*-2*	*-4*	*0.071*
Active mode infr.	*1/5*	*1/3*	*1/-2*	*1*	*-3*	*0.088*
Brussels scenario	*1/2*	*1/-2*	*1/-4*	*1/-3*	*1*	*0.261*

Consistency ratio: 0.03

3.3.6. Greenhouse gas emissions

Mobility related greenhouse gas (GHG) emissions are directly related to the fuel combustion process. The amount of emitted GHGs is determined by vehicle speed, driving style, road layout properties, engine performance and road construction techniques.

30-km/h speed regimes have a significant impact on fuel consumption and GHG emissions. Vehicles consume more fuel per km at low speed, since the optimal fuel consumption level is situated between

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Speed reducing devices, sinuous road layout and grade-separated intersections impede the speed persistence of vehicles. The obtained moderated and inhibited vehicle speeds entail a higher level of fuel consumption and increasing GHG emissions (Ahn and Rakha, 2009). Active mode infrastructure, on the other hand, allows for emission free mobility.

One important and often ignored aspect in considering mobility related GHGs are the gasses emitted during the road infrastructure construction phase. Natural gas and oil provide energy in construction plants (production of bitumen, emulsion, asphalt etc.), in construction vehicle engines (pavers, rollers, etc.) and in transport vehicle engines (trucks, locomotives, etc.). The European Environmental Agency's EMEP/CORINAIR Emission Inventory Guidebook specifies GHG emission limits for transport related industrial activities, i.e., cement/asphalt production, road transport activities and other mobile sources and machinery activities (Huang et al., 2009). Innovative bitumen applications, generated at lower production temperatures, and construction/transportation vehicles with more efficient engines can reduce the road infrastructure related GHG emissions.

Within the Brussels Capital Region, the road transport sector is responsible for about 1/5 of the total emitted GHGs. These road transport related GHG emissions remained stable between 1990 en 2008, with an average annual share of 722.9 tonne CO_2 equivalent (BIM, 2012b). Vehicle speed at 30-km/h in the central pentagon can amplify the road transport related GHG emissions within the Brussels Capital Region. However, no exact figures were found.

As a result of the potential GHG's emitted during the mobility activities and during the construction phase, the alternatives are lexically ranked: reconstructing roads and intersections < speed inhibitors < Brussels pentagon scenario < 30-km/h speed regimes < active mode infrastructure. Table 9 translates the ranking into a comparison matrix to compute the eigenvalues.

TABLE 9. COMPARISON MATRIX AND EIGENVECTORS FOR GREENHOUSE GAS SUB-CRITERION. SOURCE: OWN SET UP

	30-km/h regime	*Speed inhibitor*	*Recon. roads / inters.*	*Recon. active mode infr.*	*Brussels pent. scenario*	*Eigenvectors*
30-km/ regime	*1*	*3*	*4*	*-2*	*2*	*0.263*
Speed inhibitors	*1/3*	*1*	*2*	*-4*	*-2*	*0.097*
Roads / intersect.	*1/4*	*1/2*	*1*	*-5*	*-3*	*0.062*
Active mode infr.	*1/-2*	*1/-4*	*1/-5*	*1*	*3*	*0.419*
Brussels scenario	*1/2*	*1/-2*	*1/-3*	*1/3*	*1*	*0.160*

Consistency ratio: 0.02

3.3.7. Application material

The 30-km/h speed regime requires informative traffic signalisation. No studies have been found on reusing or recycling traffic signs. However, the Flemish Traffic Sign Database project, embedded in the European Rosetta project, registers all posted traffic signs in Flanders. In addition to general registration, possibilities are investigated to maintain, repair and renovate traffic signs.
The implementation of speed inhibitors and the (re-) construction of roads, junctions and active mode infrastructure require concrete. Industrial by-products like coal fly ash, coal bottom ash and recycled concrete pavement (RCP) can be used for producing concrete, as substitutes for natural aggregates. However, no guidelines specify the incorporation of by-products in the production of concrete. The integration of fly ash and bottom ash in the production process is attractive regarding its price, reduced GHG emissions and low acidification rate. Still, if the transportation distance ratio of coal fly/bottom ash to the natural aggregates is more than 1/3, the usage of coal fly/bottom ash will result in more energy usage, CO_2 emissions and a higher acidification potential. Using RCP as substitute increases CO_2 emission and increases the acidification potential, in relation to natural aggregates. Nevertheless, if the transportation distance ratio between RCP and natural aggregates is more than 1/4, RCP is found to be more energy effective and to emit less CO_2, in relation to natural aggregates (Chowdhury et al., 2010).
No specific data on the recycling of application materials for 30-km/h policies in the Brussels pentagon has been found. Still, the informative 30-km/h measures require less material than the infrastructural policies.

The alternative policies are lexicographically ranked according their required application material: reconstructing roads and intersections < active mode infrastructure < speed inhibitors < Brussels pentagon scenario < 30-km/h speed regimes. Linking the ranking to a 9-point scale enables the intercalation of relative scalars in a comparison matrix (table 10), ensuing in the eigenvalues per alternative for the application material criterion.

TABLE 10. COMPARISON MATRIX AND EIGENVECTORS FOR APPLICATION MATERIAL SUB-CRITERION. SOURCE: OWN SET UP

	30-km/h regime	*Speed inhibitor*	*Recon. roads / inters.*	*Recon. active mode infr.*	*Brussels pent. scenario*	*Eigenvectors*
30-km/ regime	*1*	*3*	*5*	*4*	*2*	*0.420*
Speed inhibitors	*1/3*	*1*	*3*	*2*	*-2*	*0.162*
Roads / intersect.	*1/5*	*1/3*	*1*	*-2*	*-3*	*0.066*
Active mode infr.	*1/4*	*1/2*	*1/-2*	*1*	*-3*	*0.099*
Brussels scenario	*1/2*	*1/-2*	*1/-3*	*1/-3*	*1*	*0.252*

Consistency ratio: 0.0

3.4. AHP results

Each alternative is pairwise compared towards the other alternatives, in relation to each sub-criterion, based upon the lexicographic ranking derived from the indicators (section 3.2). Next, the eigenvalues for each alternative are computed per sub-criterion, while the consistency in the priority setting is verified; as described in step 2c and 2d of the methodology (section 2.3). To avoid deficiencies in the arithmetic operations, the Expert Choice® software programme is used calculate the eigenvalues, to verify the consistency and to aggregate the eigenvalues according the weights of the criteria. As a result, the alternatives are ranked in priority matrices, which are illustrated by performance sensitivity figures per criterion (Figure 3-6).

The coloured (dashed) axes in the performance figures represent the alternative 30-km/h alternatives, which intercept the vertical assessment criteria axes, illustrated on the lower vertical axis. These intercepts exemplify the outcome of the pairwise comparison, which are expressed as eigenvalue scores in percentages on the far right vertical axis. The sum of the different alternatives scores is equal to 100%. The overall vertical axis aggregates the eigenvalue scores per criterion in overall eigenvalue scores per alternative. The rectangular beams signify the weights of the criteria, which are expressed in decimals on the far left vertical axis. The sum of the weights per criterion is equal to 1.

3.4.1. Social criteria

Figure 3 illustrates the priority ranking of the policy alternatives towards the social sub-criteria. Speed inhibitors are socially the most preferable policy alternative (34%). Speed inhibitors contribute considerable to the traffic safety sub-criterion, allocated a weight of 0.727 compared to 0.182 and 0.091 for the city liveability and social inclusion respectively. (Re-) Constructing active mode infrastructure is however more beneficial for the city liveability, since active displacements reduce pollutant gas and noise emissions. Active mode infrastructure includes in addition multiple possibilities to warrant safe mobility for excluded vulnerable groups.

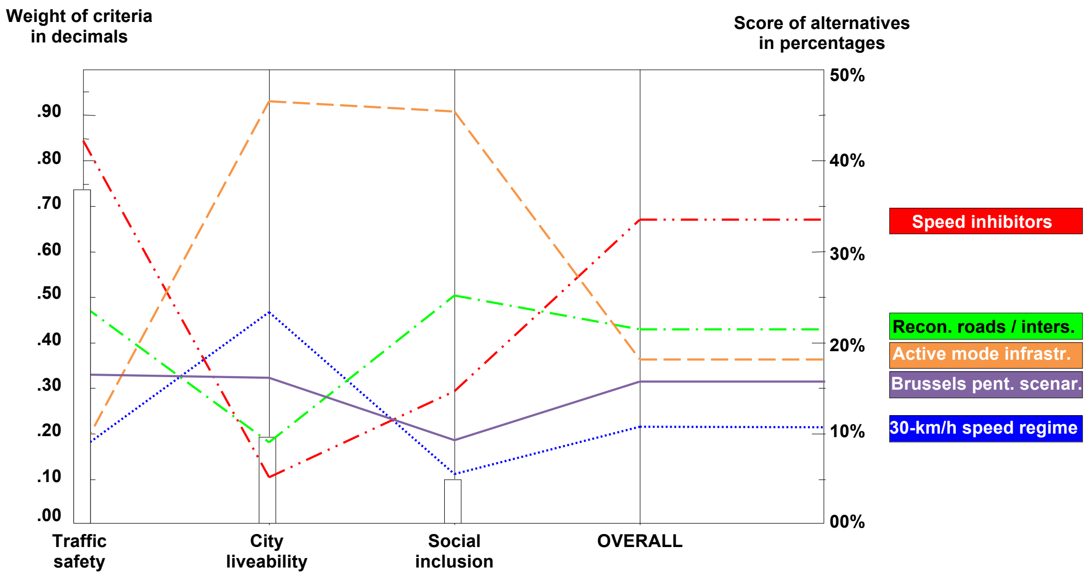

FIGURE 3 - PERFORMANCE OF THE SOCIAL CRITERION PER SUB-CRITERION. SOURCE: OWN SET UP IN EXPERT CHOICE

30-km/h speed regimes is socially the least preferable general policy (10.5%). Poor traffic safety effects, increasing pollutant gas emissions and no specific prospects to include vulnerable road users result in a poor performance. The empirical Brussels pentagon scenario is disclosed as second least preferred alternative (16%) on the ground of poor traffic safety effects, limited contributions to city liveability and minimal possibilities to include vulnerable groups.

3.4.2 Economic criteria

The economic performance of the 30-km/h policy alternatives is exemplified in Figure 4. Active mode infrastructure is economically the most beneficial alternative (42%) based on the high-included potential to provide access to active road users. 30-km/h regimes are from a public expenses point of view however more interesting. Still, as the accessibility sub-criterion is weighed 0.889 towards 0.111 for the public cost sub-criterion, the active mode infrastructure policies are preferred over the 30-km speed regime policies. Few possibilities to enhance the accessibility-based mobility render the speed regime alternative an overall value score of 9%.

(Re-) Constructing roads and intersections is from economic point of view the second most interesting general policy strategy (22.5%), considering the above average provision of accessibility to active road users and the high implementation costs. The empirical Brussels pentagon scenario is revealed as second least beneficial alternative (11.5%), providing no substantial accessibility merits to active and public transport road users.

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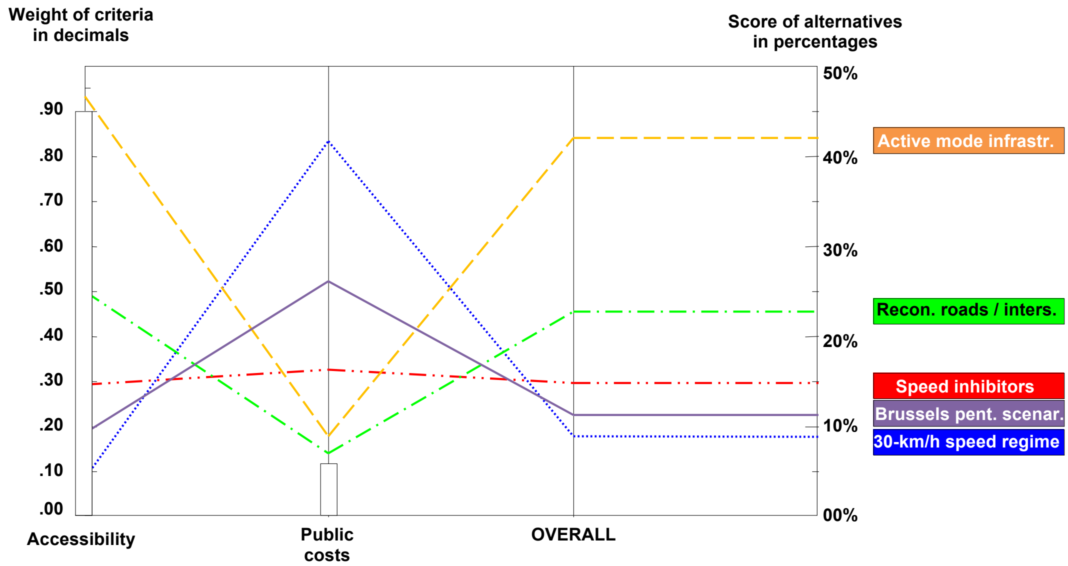

FIGURE 4 - PERFORMANCE OF THE ECONOMIC CRITERION PER SUB-CRITERION. SOURCE: OWN SET UP IN EXPERT CHOICE

3.4.3 Ecological criteria

The general 30-km/h speed regime policy (40%) and the empirical Brussels pentagon scenario (24%) are ecologically the most credible alternatives, as illustrated in Figure 5.

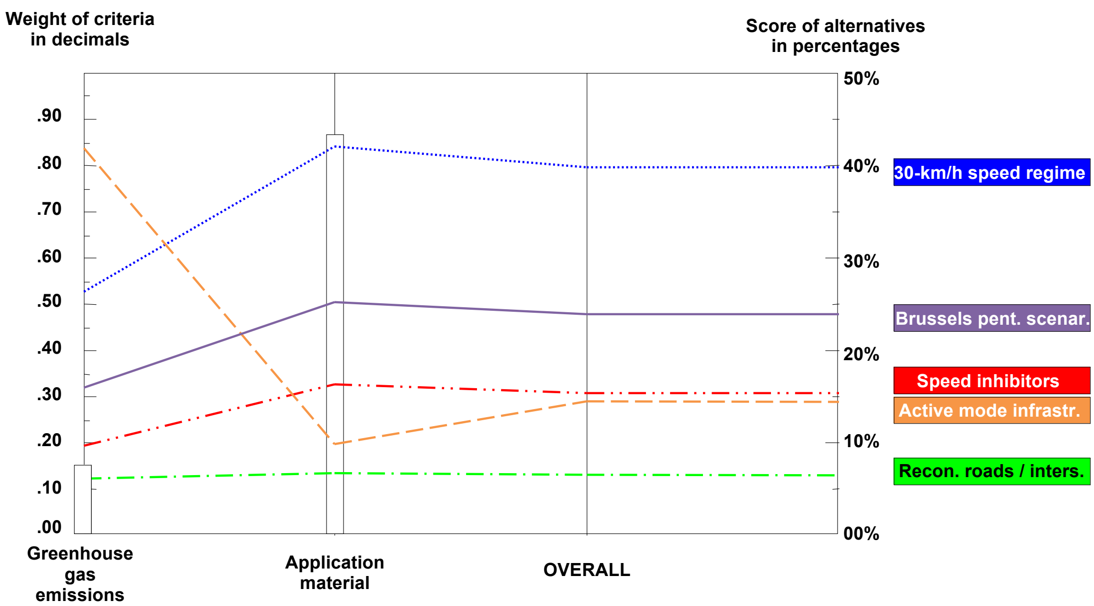

FIGURE 5 - PERFORMANCE OF THE ECOLOGICAL CRITERION PER SUB-CRITERION. SOURCE: OWN SET UP IN EXPERT CHOICE

Both alternatives require a minimal amount of application material, which is weighed 0.857 in comparison to 0.143 for the greenhouse gas emissions sub-criterion. As active mode facilities contribute to GHG-free mobility, 30-km/h speed regimes and the Brussels pentagon scenarios retain the second and third highest performance towards greenhouse gas emissions, regarding the limited amount of greenhouse gasses during the construction phase.

(Re-) Constructing roads and junctions is found to be the least credible ecological alternative (6.5%). While sinuous road layout and altered junctions enhance motorised mobility related GHG emissions, the scope and severity of the (re-) construction process amplifies road construction related GHG's. Heaps of application material is required to reconstruct roads and intersections compared to the residual 30-km/h alternatives.

3.4.4. Overall objective

Figure 6 aggregates the overall ranking per assessment criterion in an overall sustainability ranking for each alternative. (Re-) Constructing active mode infrastructure is found to be the most interesting general policy alternative with respect to sustainability (29%). The high economic and intermediate social and ecological performances ascertain the first place in the priority ranking. The competent decision-makers weighed the economic criterion with 0.489 in favour of the social (0.444) and ecological (0.067) criterion. The speed inhibitor alternative takes the second place in the priority ranking (24%), being slightly preferred over an almost equally well performing (re-) constructing roads/intersections alternative (21%). The empirical Brussels pentagon scenario (14.5%) and the general 30-km speed regime (12%) are found to be the least plausible alternatives towards sustainability based on their low social and economic performance.

A scenario analysis of the ranking results[2] illustrates that the overall ranking remains robust until the criteria are modified up to 0.609 for the social criterion and 0.343 for the economic criterion (see Figure 7). This adjusted weigh allocation makes speed inhibitors the most interesting alternative, with reconstructing active mode infrastructure and reconstructing roads and junctions as second and third most credible options respectively. Preferring the economic criterion until 0.624, while reducing the social criterion to 0.326, maintains the reconstruction of active mode infrastructure as most attractive alternative, but reduces the credibility of speed inhibitors in the benefit of the reconstructing roads and junctions' alternative. Increasing the weight for the ecological criterion as far as 0.470, while reducing

[2] See part 4.2 for a discussion on the robustness of the ranking results

the economic criterion to 0.278, ensues in 30-km/h speed regime as being the most interesting alternative.

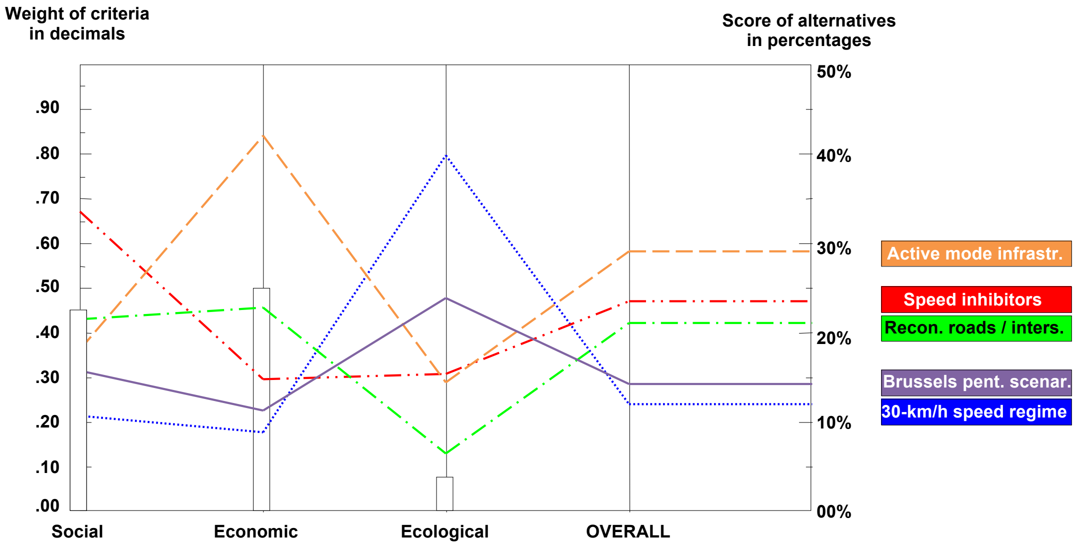

FIGURE 6 - PERFORMANCE OF THE OVERALL OBJECTIVE PER CRITERION. SOURCE: OWN SET UP IN EXPERT CHOICE

3.5. Implementation pathways (step3)

The sustainability performance of the empirical Brussels pentagon 30-km/h scenario can be enhanced by the additional implementation of general measures such as: active mode infrastructure, increasing speed reducing devices and the (re-) construction of roads and intersections (see priority ranking Figure 6). Completing the current informative 30-km/h zone, consisting of 30-km/h signalisation, display speed cameras and limited speed inhibitors, with supplementary walk and cycle infrastructure will provide access to a larger quantity of travellers, incite emission free mobility and advance inclusive urban mobility. Additional speed reducing devices will, at the same time, reduce collision by compelling appropriate vehicle speed for low implementation costs.

Information gathered in previous methodological steps, such as the assessment criteria, the indicators and the measurement units strengthen the development of implementation pathways. Elements like social inclusion, greenhouse gasses emitted during the road construction phase and the application of recycled or recyclable application materials contribute to the sustainable implementation of the Brussels 30-km/h scenario. A frequent occurring problem in the implementation of infrastructural projects is the gap between the preparation studies and the actual implementation of the scenario, which is often fulfilled by divergent governmental departments. Clear communication between the study departments, the public executive departments and the subcontractors contribute to the desirable implementation of the empirical scenario.

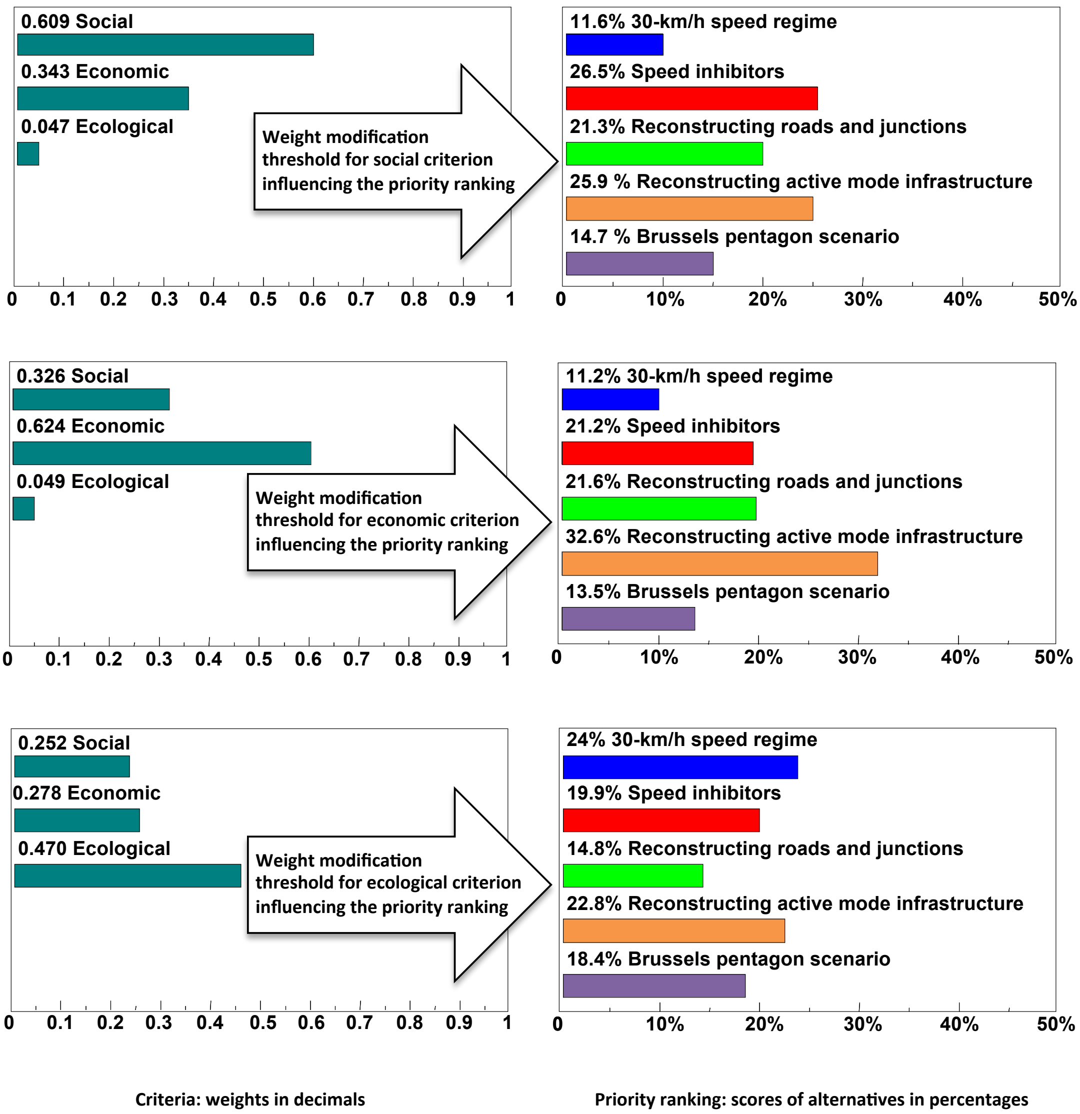

FIGURE 7 - SCENARIO ANALYSIS: EFFECT OF WEIGHT MODIFICATION ON PRIORITY RANKING. SOURCE: OWN SET UP IN EXPERT CHOICE

4. DISCUSSIONS

4.1. Contributions

The implementation of the recommended assessment approach harbours advantages for decision-making processes towards sustainability. The composite framework format, the inclusion of principal sustainability attributes, the systematisation of subjectivity and the application for the traffic safety subdomain are beneficiary for decision-processes towards sustainable mobility.

To identify the policy option with the least impact in achieving sustainability objectives, impact assessment strategies are crucial. Still, few studies consider pragmatic aspects in the development of impact assessment tools, to support the sustainability assessment of policies within governmental administrations. This paper relates an analytical evaluation framework (AHP) to a procedural SA format, to provide policy-makers not merely technical details on the merits and drawbacks of policy alternatives, but to stimulate contemplation on the nature of the decision problem and the procedures to reach/implement assessment decisions as well. The majority of studies on the assessment of sustainable decision-processes focus either on the analytic evaluation or on procedural evaluation. For example, Lebre La Rovere et al. (2010) and Doukas et al. (2007) provide an extensive sustainability assessment of energy scenarios and technologies, but offer no procedural perspectives to realise the scenarios. Other studies improve the implementation process of sustainability evaluations, but provide no technical specifications to assess the actual impact (see for example Carter et al., 2009; Rozema et al., 2012). The comprehensive assessment format proposed in this paper provides policy-makers with a ready-to-use evaluation framework to conduct sustainability assessments. Similar tools support the probability of being actually integrated in the decision-process and bridge the gap between the design of sustainability assessment instruments and the public use (see McIntosh et al., 2008).

The assessment attributes in this AHP application are weighed according the preferences of the competent decision-makers. The selected attributes represent in addition the three principal dimensions of sustainable development. Sharifi and Murayama (2013) conclude in an extensive review on sustainability assessment tools, that many assessment instruments frequently ignore social and economic aspects. This application relates therefore each sub-attribute to the social, economic or ecological dimension, to perpetuate the three general principles of sustainable development (WCED, 1987) in the assessment process (see section 3.1.1). Other studies configure their assessment criteria in a less specific manner. Chatzimouratidis and Pilavachi (2009) structure the AHP criteria for the evaluation of power plants in a technology/sustainability criterion in contrast to an economic criterion. Hence, the focus of their evaluation is economically biased, since they relate no clear sub-attributes to the social neither the ecological dimension. This paper propagates the structuring of assessment criteria according the principal dimensions of sustainable development, to emphasise the intrinsic sustainability objective of the evaluation.

As subjectivity is inherent in every decision, the ambition of multi-criteria approaches is to make subjective values and preferences explicit (value judgements), which are equally integrated with objective predictions (measurement procedures) in the analysis. Not all the subjectivity is however eliminated, but the trade-offs that the decision-makers are willing to make, are reflected in the specific context (De Lange et al., 2012). The multi-criteria procedures systemise the inevitable subjectivity by making the analytic evaluation process as transparent and reproducible as possible (Bossel, 1999).

The present paper proposes an assessment approach that has been applied for traffic safety, a particular sub-policy of mobility policies. Assessing the impact of mobility sub-policies offers alternative perspectives on decision-processes towards sustainable mobility. Wegman et al. (2012) refer to the predominant vehicle oriented standpoint of traditional mobility impact studies, which ignore relevant features for active road users. Changes in active modal split, accessibility for active modes and traffic safety feelings of active road users are frequently ignored. The assessment in this paper was therefore conducted from an accessibility-based perspective (Ratner and Goetz, 2013), which considers access to goods, services and activities in a broader context of opportunities. An extensive consideration of mobility policy-constituents and their target group (in this case active road users), offers alternative perspectives in achieving decision-processes towards sustainable mobility.

4.2 Constraints

In applying the AHP for the sustainability assessment of 30-km/h alternatives, we identified theoretical constraints, which require special attention in acknowledging the robustness and the interpretation of the final assessment outcome. The overall ranking of the policy alternatives towards sustainability (Figure 3.5) should not be considered as an absolute ranking, but as a provided structure in the most credible sustainable alternatives, based on (1) the selected assessment criteria, (2) the criteria's attributed weights and (3) the subtopics covered by the criteria, which still (4) include some degree of uncertainty regarding the consequences of the judgemental input.

The selected criteria and their respective weights are decisive in the alternatives' final sustainability performance. The assessment criteria provide the assessor with the primary source of information in comparing two alternatives towards each other. The established reference framework in the first methodological step (section 3.3.1), allows the selection of distinctive assessment criteria to address the decision problem. Multiple governmental actors can in addition be selected to weigh the assessment attributes, exerting a decisive influence on the final ranking. As such, iterative assessments can cover additional and/or differentiated assessment criteria, of which the weights can be modified according the preferences of one ore more stakeholders (Macharis et al., 2010).

The number of sub-criteria (per criterion) and the covered subtopics affect the mutual influence of the sub-criteria on the final ranking. The social criterion in our application includes an additional sub-criterion compared to the economic and ecological criterion, implying that the individual economic and ecological sub-criteria weigh more on the final ranking than the social sub-criteria (see Figure 2), regardless the allocated weights. This phenomenon also referred to as the splitting bias, requires the overall weight of an attribute to be higher, the more sub-attributes are covered by the parent attribute (Sorvari and Seppälä, 2012; Bell et al., 2003). Specific sub-attributes in our application, i.e., *greenhouse gas emissions* and *city liveability* involve in addition more subtopics than the other sub-criteria (see indicators and units in table 3.2). The *greenhouse gas sub-criterion* comprises vehicle GHGs and road construction GHGs, while the *city liveability sub-criterion* aggregates four subtopics (pollutant gas and noise, emitted by vehicles and during road construction). As these composite sub-criteria obtained lower weights compared to their sibling sub-criteria, covering only a single attribute, the influence of the sub-attributes in these composite sub-criteria is especially underrepresented in the final ranking. The splitting bias can be precluded by informing the decision-maker about the number of sub-attributes covered by the criteria and their individual sub-criteria, in the allocation of the weights.

Uncertainty about the choice for a particular option and the risks attached to the consequence of that specific option is embedded in the decision-making process. Multi-criteria analysis includes different formats to systemise these knowledge deficits in order to maximise the value of making a particular choice. The literature distinguishes between internal and external uncertainty (Catrinu and Nordgard, 2012; Gervasio and da Silva, 2012). Internal uncertainty is related to the decision problem formulation and the required judgemental input to define the decision problem, which can be solved by elaborating on the problem structure and by verifying the sensitivity of the weights in relation to the robustness of the results (Stewart, 2005). Our application relates the hierarchically structured decision problem to a strategic reference framework (section 3.2.3 and 3.1) and substantiates the robustness of the results by means of weight modifications in a scenario analysis (section 3.3.4), to preclude risks related to the selection of the assessment attributes, the alternatives and the weights of the attributes. External uncertainty arises when the consequence of an action is unknown because they depend on future events, lying beyond the control of the decision-maker (Dubrach and Stewart, 2012). External uncertainty can be treated by building a utility function, which aggregates all the individual attitudes of the decision-makers towards possible risks attached to the pairwise comparison of the alternatives (Keeney, 1977). Uncertainty related to the consequences of the pairwise comparison is in our application is not explicitly considered since the practical construction of the utility function, which identifies the objectives of the decision-makers towards the risks involved in every pairwise judgement, is a complex task. Uncertainty in the choice between a pair of alternatives can however be substantiated by applying the stochastic dominance mechanism or Monte-Carlo simulation (Dubrach and Stewart, 2012; Stewart, 2005).

5. CONCLUSIONS

The contribution of this paper was to present a pragmatic framework for the impact assessment of 30-km/h policy strategies, in order to enhance the practical performance of sustainability assessments. Linking the analytical evaluation framework (AHP) to the procedural SA decision structure stimulates the assessor to frame the decision-problem in a strategic crosscutting policy context. As a result, the alternative policies are ranked according their merits and drawbacks towards sustainability and pathways to reach and implement assessment decisions are identified. This composite format hands policy-makers a ready-to-use evaluation instrument in order to narrow the gap between policy impact assessment framework design and actual usage. The framework specifies the assessment attributes additionally according the principal domains of sustainable development and makes the subjective values and preferences in the decision-making process explicit, being beneficiary for decision-processes towards sustainable mobility.

The proposed framework has been applied for the empirical case of the Brussels pentagon 30-km/h scenario, of which the sustainability performance is compared to four general 30-km/h policy alternatives, i.e. 30-km/h speed regimes, speed reducing devices, (re-) constructing roads and junctions and (re-) constructing active mode infrastructure. The final priority ranking disclosed active mode infrastructure and speed inhibitors as most credible sustainable alternatives, based on the selected assessment attributes, which were weighed by the City of Brussels competent Department for Urbanism and Architecture. As the current Brussels pentagon scenario comprises predominantly informative measures to compel the 30-km/h regime, the sustainability performance scenario can be enhanced by the implementation of active mode infrastructure and additional speed inhibitors. As the speed inhibitors benefit the traffic safety performance, the active mode infrastructure incites emission free mobility and provides access to a larger quantity of travellers, which benefits liveability and prospective short journeys in urban areas.

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