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Policy-makers of today’s transportation investment projects engage in dialogues and debates in which the reasonableness and clarity are of great value. In the traditional transportation systems planning practices, different stakeholders reason and provide evidence in support of their preferences, but these opinions are often conflicting and rarely consistent. This paper presents a decision-aiding approach for finding a transportation alternative that best achieves the project’s goals and also indicate the level of satisfaction of different stakeholders. The proposed approach applies (i) a reasoning map to structure how experts and citizens perceive the alternatives for achieving the project’s goals, and provides (ii) belief measures in evidence theory to what extent the alternatives achieve the goals of different stakeholders. This method gives three kinds of results. First, the degrees of goal achievement can be calculated for different stakeholders. Second, the integrity of the reasoning and the quality of information are both evaluated based on measures of uncertainty associated with this information. Finally, the critical reasoning links that matter most significantly to goal achievement can be identified by means of sensitivity analysis. The paper applies the proposed method to evaluate a Streetcar alternative against Bus Rapid Transit alternative in a real-world transit alternatives analysis. The reasoning-building process provides means for the planners and citizens to present their own logic and justifications. This promotes focused discourse among different stakeholders and enriches the quality of the planning and decision-making process.
1. INTRODUCTION

Planning and decision-making of transportation systems is a multidisciplinary process governed by laws. In the U.S. SAFETEA-LU requires the consideration of a set of factors that reflect the social benefits, costs and impacts. Policy-makers engage the public in planning process, which both informs the public and reflects public purposes and needs through inclusion of stakeholder input. This makes transportation planning and evaluation processes complex and require reasonableness and clarity of judgment.

The transportation planning is a deliberative process of negotiation and consensus building that is supported by rational analysis. Decision-making about a public transportation system is not straightforward and requires negotiations. Often planning cannot advance because there is no consensus with regard to the goals and expected outcomes of the project.

This study considers the planning of public transportation investment projects as a reasoning-building process to advance a desirable course of actions. A series of actions which achieve goals give details of chained relations in a reasoning structure. The study approaches public transportation decisions as decisions under uncertainty. Transportation analysts and planners have incomplete knowledge or lack of information.

This study proposes a new goal-oriented transportation decision-aiding approach that models decision systems in a logical manner and employs available even if uncertain knowledge and inconsistent opinions in supporting decision-making. Section 2 comments briefly on the current multi-criteria decision-making methods. Section 3 reasons the theoretical basis of the approach to multi-criteria evaluation advocated in this paper. Section 4 details the practical steps for applying the method and Section 5 gives an example application. Section 6 interprets the results and discusses the intellectual merits of the approach. Section 7 concludes.

2. CURRENT PRACTICES AND THEIR ISSUES

Multi-criteria decision-making approaches have been applied for evaluating transportation investment projects since 1970s. In a large-scale transportation decision problem, traditional transportation planning and evaluation approaches are constructed with a decision tree structure where the transportation system is decomposed into independent subsystems and the attributes of a system are modeled in a hierarchical tree structure.

The tree structure has been favored by many planners and analysts because of its visualization of the decision problem, and the simple mathematical operator used in the analyses. However, it requires several simplifications and assumptions. First, the tree-structure presents a classification of attributes, but it does not present the dependent relationships between them and their positive and negative effects. Second, the hierarchical structure cannot handle redundancy of attributes when one attribute belongs to two categories. This redundancy is common and always present in real-world problems. Third, the assignment of the values to the weights is problematic. The weight can represent either an absolute value which the attribute contributes to its class, or the importance of one attribute relative to another attribute in the same class.
a tree structure it is difficult to measure or compare the degree of contribution or the degree of
importance when two attributes are subjective, have different units, or are redundant. The linear
scoring method leaves room for “strategic inputs” in assigning the weights. The Analytical
Hierarchy Process (AHP) method gets around the weighting problem by pair-wise comparisons;
but, the issues of redundancy and interdependency remain. (6)

The traditional transportation system or project evaluation approaches do not have transparent,
sufficient and clearly reasoned justifications for preferring a specific transport alternative in
situations, which involve complicated chains of reasoning, uncertainty about information and
limited understanding. This is for three reasons:

First, there is insufficient knowledge about the relevant variables to build up chained reasons for
outcomes or goal attainment. Second, none of the traditional transport planning and evaluation
approaches structure the problem in such a way that the reasoning process can be modeled. They
simplify the problem, and are sometimes considered a “black box” where the inputs and the
relations between inputs and outputs are not fully described or are results of imagination. Third,
in reality, the goals and performance of alternatives are assessed and presented both in
quantitative and qualitative terms in a decision table format. In sum, without full knowledge and
information it is simply not possible to justify decisions using the traditional approaches. The
important question is how reliable are the values and judgments in the decision table and how
much they can be trusted. In the sequel, these values are called the measures of strength of
evidence for goals and performance.

Transport analysts and planners develop implicit reasoning chains when evaluating transport
alternatives; but, that reasoning is unstructured and undocumented. This causes difficulties in
understanding the bases of decision-making because there are no measures for inconsistency,
conflicts, and omissions without reference to the complexity of the problem. Therefore, in
practice, the evaluation and planning approaches are not enough for communicating decisions
because the (supposed) decision variables and criteria are not supported in a fact-based manner.

This paper views evaluation of transportation alternatives as a complex reasoning process, which
consists of various elements of both transportation and non-transportation nature and involves
diverse groups of stakeholders.

3. CONCEPTS OF REASONING-BUILDING PROCESS

A transportation decision problem consists of three components: objectively defined
transportation alternatives (supply side); the demand side comprising behavioral and
socioeconomic factors; and subjectively defined goals and objectives of the project (7). How to
explain the inter-relationships between these three is very challenging. The study proposes a
reasoning-building process and applies the following two concepts in reasoning process.
3.1 Mapping Structure for Reasoning Process

A reasoning map is constructed for evaluating the alternatives. It consists of boxes connected with links, which present the chain of reasoning of a collection of propositions and describe the presumed cause-and-effect relationships among them (8-10). For evaluating transportation alternatives, the reasoning map connects the set of transportation system characteristics to the project’s goals and the relationships between the two are described by a series of performances and impacts as shown in Figure 1. The reasoning map is useful in decision analysis because it is easy to explain and is applicable in brainstorming and clarifying issues and uncertainties.

In Figure 1, the variables (boxes) are classified into four categories. Decision variables ($D_i$) present the physical and operational characteristics of transportation alternatives such as right-of-way, vehicles, propulsion system, stations, and control and management systems. Exogenous factors ($E_i$) present attributes that are not part of the alternatives but affect the system performances, such as predicted travel demand, and land use characteristics (transit oriented development, TOD, can be made part of the $D_i$’s). Consequences ($C_i$) present the expected performances and impacts of transportation system, such as level of service, accessibility, air pollution emission. Goals ($G_i$) boxes present the goals of the transportation project.

3.2 Mathematical Formalisms for Reasoning

3.2.1 Representing Knowledge and Belief Distributions

Using the reasoning map, two knowledge representations are needed from (expert) opinions and data sources. The first is knowledge about the inputs (decision variables and exogenous factors in Figure 1), and the second is knowledge about the causal relations (links in Figure 1.)

Knowledge about inputs and relations is presented by the belief value (or the strength of evidence). The initial values of the truth of the inputs and the relations are subjective and expressed by stakeholders or predicted by the analysts. In evidence theory the belief value, $m$, is
expressed by a value between 0 and 1 (11). It presents the belief distribution across the states of outcome (or the degree that each state of outcome is supported.) The belief distributions of the input \(X\) and causal relation \(X \rightarrow Y\) is expressed:

\[
\sum_{X_i \in X} m(X_i) = 1 \quad (1)
\]

\[
\sum_{Y_j \in Y} m(X_i \rightarrow Y_j) = 1 \quad (2)
\]

where \(X_i\) and \(Y_j\) are the possible states of outcome of sets \(X\) and \(Y\), respectively. \(m(X_i)\) is the belief value (or the strength of evidence) of the state \(X_i\) of set \(X\). The causal relation \(m(X_i \rightarrow Y_j)\) is the belief value that the state \(Y_j\) of set \(Y\) will be the outcome given that the input \(X\) is \(X_i\). Equations (1) and (2) respectively imply the exhaustion of belief values of all states of outcome in input \(X\) and all states of outcome in output \(Y\) given the input \(X\), that is, they must sum up to 1.

For the input “\(X\) is \(X_i\)”, the knowledge is specified by the belief value \(m(X_i)\). For example, if belief value of the premise “the service headway of Bus Rapid Transit is short” is 0.80, then \(m(\text{Short}) = 0.80\), or that “the operating speed of Light Rail is high” is 0.60, then \(m(\text{High}) = 0.60\).

For the relation “If \(X\) is \(X_i\), then \(Y\) is \(Y_j\),” knowledge is specified by attaching the belief value associated with causal relation \(X \rightarrow Y, m(X_i \rightarrow Y_j)\). For example, a belief value for causality “if the population density along the transit line is high, then transit ridership is high” is 0.75.

The proposed method is an extension of the traditional Bayesian reasoning method (12). However, the belief value in evidence theory is not the same as the probability value in probability theory. Uniqueness of the belief value in evidence theory is its ability to specify ignorance or “I don’t know (IDK)”. This is common in transportation planning when stakeholders or analysts are not sure whether the outcome is \(X_i\) or not \(X_i\). Knowledge as “I don’t know (IDK)” is conserved in the proposed approach.

3.2.2 Mechanism for Aggregating Opinions

Given multiple stakeholders in the planning process, knowledge from different experts (or stakeholder groups) is combined by using Dempster’s rule of combination (DRC). DRC is an aggregate operator in evidence theory used for combining two belief distributions (13, 14). Let \(m_1(X)\) and \(m_2(X)\) be the belief distributions of a variable \(X\) from two experts where the outcomes of \(X\) can be specific or non-specific, e.g. Low, Medium, High, or “I don’t know”.

Equation (3) combines the belief distributions of \(X\) from two experts (or stakeholder groups), \(m_1\) and \(m_2\).

\[
m(X_i) = \frac{\sum_{X_U, X_V | X_U \cap X_V = X_p} m_1(X_U) \cdot m_2(X_V)}{1 - \sum_{X_U, X_V | X_U \cap X_V = \emptyset} m_1(X_U) \cdot m_2(X_V)} \quad (3)
\]
In Equation (3), the numerator is the sum of the product of the belief values that supports set \( X \) assigned by (two) experts. The denominator is a normalizing factor which is the sum of the product of the belief values associated with all the possible combinations of knowledge that are not in conflict. In other words, it excludes the conflicting outcomes in the calculation. \((13-14)\)

When two opinions support each other, the aggregation results in the higher belief value of the given outcome. For example, if two stakeholders, say “Experts” 1 and 2, both say “the population density will be High” with the belief value, \( m(\text{High}) = 0.80 \) for both and \( m(\text{IDK}) = 0.20 \) for both, then after combining the two opinions the new belief value for \( m(\text{High}) = 0.96 \) (and \( m(\text{IDK}) = 0.04 \)). Thus, with (new) consistent evidence, the belief value of \( m(\text{High}) \) increased (or strengthened).

When two opinions are conflicting, the aggregation results in the compromising belief value between the two. For example, if two “Experts” are in conflict—for “Expert 1” \( m_1(\text{High}) = 0.80 \) and \( m_1(\text{IDK}) = 0.20 \)” and for “Expert 2” \( m_2(\text{Low}) = 0.70 \) (and \( m_2(\text{IDK}) = 0.30 \)”, then after combining the two opinions the new belief values are: \( m(\text{High}) = 0.54 \), \( m(\text{Low}) = 0.32 \), and \( m(\text{IDK}) = 0.14 \). Thus with (new) conflicting evidence, the belief value in “High population density” and that in “Low population density” are both smaller than their original belief values.

When the “I don’t know” opinion (or weak opinion) is present, the aggregation favors the “Expert” that has the stronger belief. For example, if “Expert 1” has strong belief that “the population density will be High with \( m_1(\text{High}) = 0.80 \) (and \( m_1(\text{IDK}) = 0.20 \)” and “Expert 2” has “I don’t know” opinion, \( m_2(\text{IDK}) = 1.00 \), then after combining two opinions the new belief value becomes: \( m(\text{High}) = 0.80 \) (and \( m(\text{IDK}) = 0.20 \)). Thus when the weak and strong opinions are combined, the stronger opinions would dominate the decision.

These mechanisms are intuitive and true in decision-making process. When new evidence arrives, the analysts usually recognize whether it supports or opposes the current beliefs and instead of retaining the ambiguity there is a learning process to update knowledge (or belief value); and as a result, the “IDK” opinion vanishes is diminished.

### 3.2.3 Mechanism for Inferring the Belief Values in the Reasoning Process

Given knowledge about an input \( X \) and a causal relation \( X \rightarrow Y \), the belief value of an outcome \( Y \) is calculated as follows.

\[
m(Y_j) = \sum_{X_i \in X} m(X_i) \cdot m(X_i \rightarrow Y_j)
\]

(4)

where \( X_i \) and \( Y_j \) are all the possible states of the input \( X \) and the outcome \( Y \). Using this method for inference, the belief value \( m \) can be propagated to other variables (consequences/outcomes) along the reasoning chains. More details on the belief propagation process can be found in Dubois and Prade (1988) and Kronprasert and Kikuchi (2011) \((15, 16)\).
3.2.4 Mechanism for Measuring Uncertainty

Uncertainty is the lack of knowledge (or ambiguity associated with information used). Measuring uncertainty helps identify information needs in the reasoning process. The amount of uncertainty is quantified by two measures: non-specificity measure and discord measure. These measures quantify the “bits” of information needed to find the outcome or make the decision in the binary problem. For instance, it needs 1 bit of information to specify the outcome when tossing a coin (Head or Tail).

Non-specificity, $N(m)$, refers to uncertainty due to imprecise knowledge. $N(m)$ increases when the belief value of “I don’t know” increases and the belief values on the specific states decreases. The discord measure, $D(m)$, refers to uncertainty due to conflicting opinions. $D(m)$ increases when the belief values of two or more states are even.

The calculation and derivation of these two measures are found in evidence theory Klir and Wierman (1999) and Klir (2006) (13, 14).

\[ N(m(A)) = \sum_{A_i \subseteq A} m(A_i) \cdot \log_2 |A_i| \]  
\[ D(m(A)) = \sum_{A_i \subseteq A} m(A_i) \cdot \log_2 \left( \sum_{A_j \subseteq A} m(A_j) \frac{|A_i \cap A_j|}{|A_j|} \right) \]

where $|A_i|$ and $|A_i \cap A_j|$ are respectively the size of the outcome set $A_i$ and the size of intersection between outcome sets $A_i$ and $A_j$. $\log_2 |A|$ is the bits of information needed to find out the solution to the binary problem.

$N(m)$ and $D(m)$ have a maximum value of the logarithm base 2 of the number of outcomes. For example, consider three outcomes: “Low,” “Medium,” and “High.” If there is total lack of knowledge about the outcomes $m(IDK) = 1$, then Non-specificity is at maximum, $N(m) = \log_2(3) = 1.585$, but because there is unanimity about it, Discord $D(m) = 0$. If the opinions supporting the three outcomes are in conflict (i.e. 0.333 each), then Discord $D(m) = \log_2(3)$ and Non-specificity $N(m) = 0$. Note that the total uncertainty measure is equal to $N(m) + D(m)$.

Table 1 (Columns No.1 to No.5) shows the increase of non-specificity measure with respect to different patterns of belief distribution. The non-specificity measure gets the lowest value when all the belief values point to single specific outcome (Column No.1), while the non-specificity measure gets the highest value in the case of complete ignorance or “I don’t know.” In this case, all the belief values are assigned to every outcome, $m(IDK) = 1$ (Column No.5).

Table 1 (Columns No.6 to No.10) shows the increase of discord measure with respect to different patterns of belief distribution. The discord measure receives the lowest value when all the belief values point to only one specific outcome (Column No.6). The discord measure receives the highest value when the belief values is uniformly distributed over the outcomes, $m(X_1) = m(X_2) = m(X_3) = 0.333$ (Column No.10).
### TABLE 1 Effect of Belief Distribution Patterns on Non-specificity and Discord Measures

<table>
<thead>
<tr>
<th>Outcome of Population density</th>
<th>Belief Value $m(X_1)$</th>
<th>Examples of Different Belief Distribution Patterns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low ($X_1$)</td>
<td>1</td>
<td>No.1 0.1 0.3 0.5 0.25 0.5 0.333</td>
</tr>
<tr>
<td>Medium ($X_2$)</td>
<td>0</td>
<td>No.2 0.1 0.2 0.25 0.25 0.5 0.333</td>
</tr>
<tr>
<td>High ($X_3$)</td>
<td>0</td>
<td>No.3 0.1 0.2 0.25 0.25 0.5 0.333</td>
</tr>
<tr>
<td>I don’t know (Low or Medium or High)</td>
<td>0</td>
<td>No.4 0.1 0.2 0.25 0.25 0.5 0.333</td>
</tr>
</tbody>
</table>

| Non-specificity measure      | 0.000 0.317 0.396 0.792 1.585 | 0.000 0.000 0.000 0.000 0.000 |
| Discord measure              | 0.000 0.385 0.785 0.632 0.000  | 0.000 0.722 0.971 1.500 1.585 |
| Total uncertainty measure    | 0.000 0.702 1.181 1.424 1.585  | 0.000 0.722 0.971 1.500 1.585 |

#### 3.2.5 Numerical Example

This section illustrates a numerical example of the three mathematical mechanisms presented in the last three sections. The first is the inference process which propagates the belief values from premises to consequences/outcomes. The second is the aggregation of knowledge of different opinions. And the third is the measuring of uncertainty of knowledge. These three mechanisms are described using numerical examples.

Consider two reasoning chains supporting economic development by a Streetcar alternative as shown in Figure 2. One argues that Transit Oriented Development ($X$) will encourage investment in the corridor ($Z$). Another argues that permanence of transit system ($Y$) will increase investment in the corridor ($Z$). The reasoning chains connect between $X$ and $Z$ and between $Y$ and $Z$. Each attribute has two states of opinions: “Agree” and “Disagree,” and “I don’t know” state is added for non-specific opinions. Knowledge (or belief values) about the two inputs $m(X)$ and $m(Y)$, and knowledge of the two causal relations, $m(X \rightarrow Y)$ and $m(X \rightarrow Z)$, are shown in Figure 2. The belief values about the outcome “Investment in the Corridor,” $m(Z)$, are calculated as follows.

Using inference method, the degrees of truth of input, $m(X)$, are combined with the degrees of truth of the relation $X \rightarrow Y$, $m(X \rightarrow Y)$ using matrix multiplication. Let $X_1$, $X_2$, and ($X_1 \cup X_2$) are “Agree,” “Disagree,” and “I don’t know” for “Transit-Oriented Development,” respectively. $Z_1$, $Z_2$, and ($Z_1 \cup Z_2$) are “Agree,” “Disagree,” and “I don’t know” about “Investment in the Corridor,” respectively. The belief value of the outcome $Z$ from the first reasoning chain $m^{(1)}(Z)$, for TOD, are calculated as follows (Figure 2)

$$m^{(1)}(Z_1) = m(Z_1 | X_1) \cdot m(X_1) + m(Z_1 | X_2) \cdot m(X_2) + m(Z_1 | X_1 \cup X_2) \cdot m(X_1 \cup X_2) = 0.52$$

$$m^{(1)}(Z_2) = m(Z_2 | X_1) \cdot m(X_1) + m(Z_2 | X_2) \cdot m(X_2) + m(Z_2 | X_1 \cup X_2) \cdot m(X_1 \cup X_2) = 0.12$$

$$m^{(1)}(Z_1 \cup Z_2) = m(Z_1 \cup Z_2 | X_1) \cdot m(X_1) + m(Z_1 \cup Z_2 | X_2) \cdot m(X_2) + m(Z_1 \cup Z_2 | X_1 \cup X_2) \cdot m(X_1 \cup X_2) = 0.36$$

Similarly, the belief values of the “Investment in the Corridor” from the second chain $m^{(2)}(Z)$ for “Permanence of Transit Service” are:
Using Dempster’s Rule of Combination, the belief values of the outcome Z (“Investment in the Corridor”) from two reasoning chains, \( m^{(i)}(Z) \) and \( m^{(j)}(Z) \), are aggregated (see the grey table in Figure 2). The combined belief value \( m(Z) \)—“Agree,” “Disagree,” “IDK”—is calculated as shown below:

\[
m(Z) = m^{(i)}(Z) \cdot m^{(j)}(Z) + m^{(j)}(Z_1 \cup Z_2) \cdot m^{(i)}(Z_1 \cup Z_2) - m^{(j)}(Z_1) \cdot m^{(i)}(Z_1) \cdot m^{(j)}(Z_2) - m^{(i)}(Z_2) \cdot m^{(j)}(Z_2) \cdot m^{(i)}(Z) \cdot m^{(j)}(Z)
\]

\[
m(Z_1) = \frac{m^{(i)}(Z_1) \cdot m^{(j)}(Z_1) \cdot m^{(j)}(Z_1 \cup Z_2) \cdot m^{(i)}(Z_1 \cup Z_2)}{1 - m^{(i)}(Z_1) \cdot m^{(j)}(Z_1) - m^{(j)}(Z_1) \cdot m^{(i)}(Z_1) \cdot m^{(j)}(Z_2) - m^{(i)}(Z_2) \cdot m^{(j)}(Z_2) \cdot m^{(i)}(Z) \cdot m^{(j)}(Z)}
\]

\[
m(Z_2) = \frac{m^{(i)}(Z_2) \cdot m^{(j)}(Z_2) \cdot m^{(j)}(Z_1 \cup Z_2) \cdot m^{(i)}(Z_1 \cup Z_2)}{1 - m^{(i)}(Z_2) \cdot m^{(j)}(Z_2) - m^{(j)}(Z_2) \cdot m^{(i)}(Z_2) \cdot m^{(j)}(Z_1) - m^{(i)}(Z_1) \cdot m^{(j)}(Z_1) \cdot m^{(i)}(Z) \cdot m^{(j)}(Z)}
\]

Using the evidence theory, the non-specificity \( N \) and discord \( D \) measures associated with the combined belief distributions of the outcome \( Z \) (“Investment in the Corridor”) are

\[
N(m(Z)) = \sum_{Z_i \in Z} \log_2 |Z_i| = 0 + 0 + 0.080 = 0.080
\]

\[
D(m(Z)) = \sum_{Z_i \in Z} m(Z) \cdot \log_2 \left( \sum_{Z_j \in Z} m(Z_j) \frac{|Z_i \cap Z_j|}{|Z_j|} \right) = 0.178 + 0.284 + 0.000 = 0.462
\]

These \( N(m(Z)) \) and \( D(m(Z)) \) values for \( Z \) add up to total uncertainty of \( 0.542 \) (\( 0.080+0.462 \)), whereas the maximum uncertainty of outcome \( Z \) is \( \log_2(2) = 1.000 \). These values imply that the opinions about the outcome \( Z \) are quite specific—\( N(m(Z)) \) is small. However, there is discord about whether there would be “investment along corridor” or not—\( D(m(Z)) \) is moderate.

![FIGURE 2 Example of the calculation process](image-url)
4. STEPS OF REASONING-BUILDING PROCESS

The steps in the proposed reasoning process for evaluating transportation alternatives are the following.

Step 1: Construct the reasoning maps to present how the proposed alternatives would influence the achievement of goals of the project.

Step 2: Assign the belief values to individual premises and causal relations by eliciting “Expert” opinions.

Step 3: Execute the model by calculating (i) the degree of achievement of each goal; (ii) measuring the integrity of the reasoning process; and (iii) identifying critical reasoning chains.

4.1 Construction of Reasoning Maps and Elicitation of Knowledge

Two steps are needed to construct the reasoning map. First, the transportation project’s goals \((G)\), the collection of variables that describe the characteristics of the systems \((D)\) and the forecast travel conditions \((E)\) are identified in the planning process. The goals (end nodes \(G\) in a reasoning map) reflect the purposes of the proposed (transit) projects. The definition of the alternatives and the project description define the variables (starting nodes \(D\) and \(E\)) in the reasoning map.

Second, the reasoning chains that determine the causalities are developed by bridging the relationships between the alternatives and the project’s goals. The chains of reasoning are developed using performance measures and arguments about alternatives (documented in the planning process). They can be input-output relations, cause-and-effect relations, or inferences for particular actions. The reasoning maps are scrutinized by experts and informed by public input before further analysis.

Once the reasoning chains are developed, knowledge (or evidence) about every premise and every causal relation in the reasoning chains are elicited from experts and planners and citizen groups. These “informants” assign belief values to every state in premise \((D\) and \(E)\) and every state in relation shown in Figure 1.

Belief in an outcome for which two reasoning chains contribute can also be aggregated using the DRC. This rule can be used for combining two belief distributions and two or more reasoning chains (points of view). It builds up the belief values (or eliminate the degree of ignorance or “I don’t know”) of stakeholders when supporting pieces of evidence are combined.

4.2 Model Execution

Once knowledge about every input to transportation alternatives and every relation in the reasoning map has been elicited, the following calculation process is performed to evaluate the transportation alternatives.
• The transportation alternatives are evaluated based on the belief values for achieving the specified goals.

• The integrity of the reasoning process is evaluated based on the measures of uncertainty, non-specificity, and discord associated with available information.

• The critical reasoning chains that significantly influence the outcome are determined based on the sensitivity analysis.

### 4.2.1 Determination of the Degree of Achievement of Individual Goals

Using the inference process shown in Equation (4), the belief values (or truth values), $m$, are propagated from the input to the consequences/outcomes all the way to the individual goals.

Once the likelihoods for achieving the individual goals, $m(G_i)$, are calculated, Belief ($Bel(G_i)$) and Plausibility ($Pl(G_i)$) measures can also be calculated, which indicate the conservative and optimistic measures of achieving the goals.

These two measures are derived from the belief distributions. $Bel(G_i)$, is measured by summing all the consistent evidence pointing to goal $G_i$. $Pl(G_i)$ is the weight of non-conflicting evidence toward goal $G_i$, obtained by summing the non-conflicting belief values for outcome $G_i$.

$$Bel(G_i) = \sum_{G_j \mid G_j \subseteq G_i} m(G_j) \quad \text{and} \quad Pl(G_i) = \sum_{G_j \mid G_j \cap G_i \neq \emptyset} m(G_j)$$

### 4.2.2 Measure of Integrity of Reasoning Process

Measuring uncertainty of information and knowledge helps identify information needs in the reasoning chains and promotes focused discourse in the decision-making process. In this step, the amount of information-based uncertainty in a reasoning chain is quantified using the non-specificity and discord measures previously described. They measure the quality of knowledge and information given to the transport analyst.

### 4.2.3 Identification of Critical Reasoning Chains

Identifying the strong and weak reasoning chains of the process is necessary to justify the validity of reasoning. This helps decision-makers determine which characteristics of alternatives affect the decision most, and provide information on how to improve the alternatives in order to improve goal achievement.

Given the belief distributions attached to each attribute in a reasoning map, one can determine the strength and weakness of the reasoning chains; in other words, one can determine whether a reasoning chain is more influential (or less uncertain) than the other chains.

To identify the critical chain in the reasoning map involves finding the variable that most influence the degree of goal achievement. This sensitivity analysis is done by comparing the degree of goal achievement when a particular variable is removed from the map with all the variables in the reasoning map (the base case).
The higher the difference between the degrees of goal achievement, the more that variable affects goal achievement. The determination of critical reasoning chains is conducted backward (from the goal node to the decision nodes) by comparing the importance measures among its preceding nodes and selecting that preceding node, which has the highest difference.

5. APPLICATION OF REASONING PROCESS TO TRANSPORTATION PLANNING

The proposed methodology to the Alternatives Analysis process was applied in a case study in an evolving public transportation investment project in Northern Virginia. The Streetcar alternative is evaluated and compared to the Bus Rapid Transit (BRT) alternative with respect to five goals of the project—mobility, economic development, livability and sustainability, multimodal transport system, and safety (16).

The reasoning map represents opinions of experts from transit and regional planning entities and allowing “I don’t know”; ideally citizen views would also be collected. The reasoning map was first drawn up by ten transport experts. The belief values, which represent the confidence of opinions associated with each causal link, were assigned next. The mechanism for propagating the belief values along the chains was applied, and the degree of belief for achieving the goals was obtained. Finally, a measure of uncertainty associated with each variable and goal was calculated to assess the quality of information and the reasons for selecting the preferred alternative.

The study presents the model results as follows. First, the reasoning map configuration is shown. Second, the degrees of goal achievement and their uncertainty measures are discussed. Finally, the critical reasons supporting the goals are determined.

5.1 Reasoning Maps for Goal Achievement

The reasoning map developed is composed of 91 variables (22 decision variables, 2 exogenous variables, 62 consequences/outcomes, and 5 goals.) For each variable (proposition), two possible states of outcomes exist: “Agree” and “Disagree.” The “I don’t know” state is added to imply non-specific opinion.

Figures 3 and 4 are examples of the reasoning map for the goal of “Improved Mobility” and “Economic Development.” The reasoning maps for the remaining goals are not shown here. The boxes on the left column present the decision variables of the transit technology, and the boxes on the right column show the goals of the project. The intermediate boxes which connect between decision variables and goals are a series of interrelated consequences and performances.

In the analyses, some variables in one map may be connected to the reasoning maps for the other goals. For example, “Increase in transit riders” is related to ‘Improved Mobility’ (Goal 1) and ‘Economic Development’ (Goal 2). To simplify the presentation these connections are not shown.
FIGURE 3 Reasoning map for achieving Mobility Goal

FIGURE 4 Reasoning map for achieving Economic Development Goal
5.2 Degrees of Goal Achievement and Uncertainty Measures

Two ‘Build’ alternatives are compared: Streetcar and Bus Rapid Transit alternatives. The belief values that the Streetcar alternative achieves the goals of the project relative to the Bus Rapid Transit alternative are evaluated.

Table 2 presents the degrees of goal achievement and their associated uncertainty measures of the Streetcar alternative relative to the BRT alternative. There is agreement among the experts that the Streetcar alternative supports most of the goals of the corridor project at high degrees of achievement: 0.803-0.953 for mobility, 0.911-0.982 for economic development, 0.949-0.999 for livability and sustainability. The exception is for multi-modal transport system, for which the agreement is low (0.149-0.352). Achieving “Safe environment” is about the same (no difference between two alternatives). The lower values of the degrees of achievement of individual goals represent the conservative values ($Bel$) and the upper values represent the optimistic values ($Pl$), the sum of belief values attached to “Agree” and “IDK.”

The high degree of consensus among the planners was not shared by the affected interest along the project corridor. In the public meetings there was a distinct division: the older people (say 45 and over) favored the BRT while the younger favored the Streetcar. There were some young renters in the meeting in whose opinion Streetcar (and TOD meant) “transit oriented displacement” and for whom the economic development in the corridor would require moving away from the city to a more affordable rent location.

<table>
<thead>
<tr>
<th>Goals</th>
<th>Degrees of Goal Achievement</th>
<th>Uncertainty Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Agree</td>
<td>Disagree</td>
</tr>
<tr>
<td>Improve Mobility</td>
<td>0.803</td>
<td>0.047</td>
</tr>
<tr>
<td>Encourage Economic Development</td>
<td>0.911</td>
<td>0.018</td>
</tr>
<tr>
<td>Promote Livability and Sustainability</td>
<td>0.949</td>
<td>0.001</td>
</tr>
<tr>
<td>Support Multi-modal Transport</td>
<td>0.149</td>
<td>0.648 $^a$</td>
</tr>
<tr>
<td>Improve Safe Environment</td>
<td>0.012</td>
<td>0.961 $^b$</td>
</tr>
</tbody>
</table>

$^a$ It is not believed among experts that Streetcar would support multi-modal transport compared to the BRT.

$^b$ It is not believed that Streetcar would provide safer environment than BRT. The safety of both Streetcar and BRT are believed to be about the same.

$^c$ The maximum uncertainty of opinions associated with individual goal is $\log_2(2) = 1.000$ as there are two possible outcomes: “Agree” and “Disagree.”

6. DISCUSSION

The proposed method may give the impression of complexity and laboriousness not worth the value of the results. Anyone who has developed the data and calculations of a benefit-cost analysis or has applied the AHP or the Bayesian method knows that impression is debatable or even moot. It also needs to be kept in mind that this was the first application of the method and improvements are possible. Two key issues arise from this study: how to use the proposed approach in a real transport planning process, and how to interpret or benchmark its results.
The proposed approach has practical value in two respects. First, it quantitatively measures the degree that the selected alternative achieves individual goals. This enables the affected interest to understand and assess the strength not only of the reasoning process, but also of the planning process and the alternatives considered. Because it incorporates the notion of “I don’t know” in the calculation of the ‘truth’, both the conservative and optimistic views of the degree of goal achievement are obtained.

The reasoning map and the associated belief values of each variable and their interrelationships help identify the critical links that made the most important contributions to the truth and the degree of achievement of the goals. Once the critical nodes and links are identified, the planners can pinpoint the relationships which should be studied more to improve the strength of the reasoning process.

6.1 Effects of “I Don’t Know” Opinions

Figure 5 shows the effects of the “I don’t know” opinion on the achievement of individual goals measured by Belief (Bel) and Plausibility (Pl) measures. The sensitivity of “I don’t know” opinion is tested by increasing the belief value of “I don’t know,” m(IDK), for all input variables from 0 to 1 with an increment of 0.1, and proportionally decreasing the belief values of other outcomes. When the “Experts” are very certain about their opinions, m(IDK) = 0, then the Belief (Bel) and Plausibility (Pl) measures are equal. When “I don’t know” increases the difference between Bel and Pl measures also increase rapidly. The Bel value decreases since evidence is less certain. The Pl value increases because it represents “optimism” about the outcome (“if you don’t know, then everything is possible”). The Bel measure is a conservative one (“if you don’t know, then it is unlikely that the possible happens”). The difference between the two measures indicates the degree of uncertainty about goal achievement.

![Figure 5](image_url)
6.2 Critical Reasons

A sensitivity analysis was performed to identify the critical link(s) that most influence the support of the Streetcar alternative. The critical chains contain the variables that highly support the belief of achieving a goal. The critical reasoning chain that influenced the most the achievement of Goal 1 are marked by (*) in Figures 3 and 4. Should there be much uncertainty in achieving a goal by a particular alternative; the critical chain would indicate where more resources should be employed to increase knowledge and to reduce the uncertainty or ambiguity.

In Figure 4, showing the ‘Mobility’ goal, Streetcar receives higher achievement than BRT because the streetcars’ ride is smoother with higher riding quality than of buses, which may be sensitive to pavement irregularities and traffic interruptions. Streetcar is also believed to be more attractive to residents, commuters, and visitors. The number of transit users would increase, and Streetcar would increase the capacity of the corridor and carry more transit passengers.

In Figure 5, showing the ‘Economic Development’ goal, Streetcar would be better than BRT. It is believed that a fixed rail infrastructure is a permanent and long-term transit investment. It would become a corridor landmark and community resource. It would bring more private investment and would encourage more economic activities along the corridor.

7. CONCLUSIONS

The principal advantages of the proposed reasoning-building process are: (i) potential to model the planners’ and stakeholders’ reasoning process in the evaluation of transportation alternatives; (ii) flexibility to handle different opinions which may be incomplete, uninformed or informed, or conflicting elicited from multiple actors; (iii) capability to measure uncertainty associated with information or knowledge to focus debates and improve analyses; and (iv) documented paper trail and record about the reasoning process leading to the recommendation for the selection of an alternative. All of these are useful for later studies and analyses about anticipated or predicted outcomes and will improve the scientific knowledge-base on how decisions are reasoned. The proposed approach clarifies transportation decision-making processes where multiple experts or actors are involved, and knowledge of individual experts is fragmented and opinions among them may be conflicting.

The possible drawbacks of the proposed approach are two-fold. First, the reasoning map can be manipulated by the analysts/planners. This manipulation is mitigated by the greater transparency of the process than in the traditional approaches in which the analysts/planners’ reasoning is not revealed in a reasoning map. It may be an advantage to the planners to know the stakeholders’ evaluations and have an opportunity to understand the concerns of stakeholders and their reasoning. It also is possible to customize the map to reflect the stakeholders’ reasoning path. This is an important issue. The advantage of the reasoning process is the possibility to separate plan development from plan evaluation based on the reasoning process. The planner can then legitimately use the reasoning map in planning by studying its weak links.
Second, the mechanism to calculate the degree of goal achievement is susceptible to ‘group think’. This indeed may have been the case in the case study project. The underlying concept of the proposed mechanism leads to believing the stronger opinions and suspecting the weaker opinions. The stronger opinions dominate the calculations. This seems to be true in any decision-making process. Therefore, for the method to be constructive, it is important that “strong beliefs” are close to the “truth” or at least frank. The other side of this issue is that opinions of the stakeholders need not be combined and the strong voice need not necessarily dominate, but even the weak voice can be heard.

It is desirable in applying the proposed reasoning-building process that several groups of stakeholders, possibly representing different views and values, are involved in planning work. The success of the proposed approach depends on the agreement on the reasoning maps and the integrity of knowledge used on assigning belief values on those maps. During the planning process, the reasoning map should be reviewed by several groups of stakeholders for reasonableness, comprehensiveness, clarity, and economy (parsimony) in carrying out the evaluation. The experts and participating citizens should speak out honestly and genuinely about their judgments and openly admit their understanding and degree of uncertainty in their opinions.

The reasoning-building process developed in the paper assists transportation planners to evaluate alternatives, to reason about the alternatives, and to measure the validity of reasoning in the evaluation. The decision model was created using the reasoning map structure and the evaluation developed using the evidence theory.

The following two observations are central and important in the context of this application. Detailed information about characteristics of the alternatives was available and considered, and professionally worked through by experts before their interviews and in drawing up the reasoning map. Significant consequences, which contribute to the goals of the project, were discussed and anticipated. They are reflected in the reasoning map and show the underlying thinking of the consulted experts. It is likely that in a real-world application a smaller reasoning map would evolve over time and would not only be justified for planning purposes, but would also clarify the decision situation.

The credibility of the proposed approach does not, however, depend only on the assignment of beliefs on the various elements of the plans. Although the experts and the participating citizens should be genuine and honest about their judgments and openly discuss about their degrees of “I don’t know,” there is value simply in drawing up the reasoning map about the plans and discuss and clarify the relationships among the plan elements.

This is important. The method can be applied partially by developing the reasoning map first. The mathematical parts can be added later if desired. In fact, conceivably, such a need for some quantification would arise spontaneously in response to curiosity about the degree of rationality of the reasoning underpinning the plan proposals. In the citizen participation meetings attended, not influenced by this paper or its authors, the participants were indeed divided into voluntary groups and asked to draw diagrams for the presumed relationships in affected planning variables and issues. The observed difficulty of the task was that the groups, which gathered around the four or five tables with maps and papers, were heterogeneous and did not represent a cohesive
interest group or neighborhood. The groups also had limited time to accomplish their task. A
more structured approach, perhaps evolved over several public meetings would likely result in a
more useful reasoning map. When applied in several planning projects, experiential knowledge
thus gathered would support the learning curve to apply the method. The mathematical processes
applied and shown in this paper are not a requirement. They can come part of the applications
later. Thus, the method would not increase the cost or duration of planning, but clarify it and
make it more focused. There also could be savings.

The proposed approach is a useful and illuminating method for transportation planning purposes
in which stakeholders can review the experts’ and decision makers’ judgments and evaluation as
a process. The method can promote focused discourse among the transportation planners and
citizens because it reveals the degree of beliefs and uncertainty, and how much trust is placed on
a proposed alternative to achieve the goals it is intended to serve or achieve.

The method, which bears similarity on Forrester’s systems dynamics (18), is useful in decision
analyses because it is easy to understand and is applicable in brainstorming and compromising. It
is forward-looking and not restricted to using quantitative models or regressions models on past
data and behavior—which can be both its strength and Achilles’ heel.

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