
Transportation corridor decision-making with multi-attribute utility theory

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Abstract: This paper provides a description of how decisions concerning transportation programmes and projects can be made in the context of sustainable transportation. It provides information on identifying appropriate performance measures for sustainable transportation and then quantifying these measures with a traffic simulation model (CORSIM) as well as transportation environmental models. The quantified performance measures were then used with three decision making methodologies. The test bed used for this study comprised a transportation corridor in Tshwane, South Africa and one in Houston, Texas. A method based on the multi-attribute utility theory (MAUT) techniques was found to be the best because a broad range of quantitative and qualitative sustainability issues can be included in the decision-making process. In addition, the disaggregate approach proposed in this paper made it possible for decisions to be made at the individual link level.

Keywords: decision making; multi-criteria; transportation corridor; multi-attribute utility theory; performance measures.

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1 Introduction

The transportation planning process includes many different objectives and reflects the wishes of wide-ranging interests. A sustainable transportation system seeks to ensure that the major issues of economic development, social equity and environmental stewardship are addressed within the transportation sector (a detailed discussion of the concept of sustainable transportation can be found elsewhere) (Zietsman, 2000). Decision-making in the context of sustainable transportation, therefore, involves the evaluation of a discrete set of alternatives while considering conflicting objectives.

Even though it is essential to use techniques that include these multiple and conflicting objectives, decision-making in the transportation sector is often performed with single-objective decision-making methodologies such as benefit-cost analysis. This paper illustrates how a multi-criteria decision-making technique, specifically multi-attribute utility theory (MAUT) can be used to make decisions regarding transportation corridors and how these decisions would differ from the decisions reached through conventional single-objective techniques.

There were two freeway corridors used for the analysis, one in a developing nation (Tshwane, South Africa) and the other in a developed nation (Houston, Texas). The corridors were divided into four sections (or links) and the objective was to decide which link combinations should be widened through the addition of an extra lane.

There were three methodologies used to illustrate their effects on the final decision. The first application used a pure net present worth (NPW) analysis, which only considered monetary benefits. The other two techniques were based on the MAUT approach, one including criteria weights and the other excluding criteria weights. The performance measures used in the MAUT approach included monetary benefits as well as negative externalities such as fuel consumption, vehicular emissions, mobility, and traffic safety.

The analyses illustrated that the type of decision-making methodology and particularly whether the full range of criteria (objectives) are included in the decision

making, have a marked effect on the final decision. The MAUT approach made it possible to include a broad range of negative externalities even though these criteria cannot be expressed in monetary terms. The decision-maker, therefore, can use the results from the multi-criteria decision-making analysis as a basis for deciding on the most appropriate alternatives, thereby allocating the scarce resources in the most effective way.

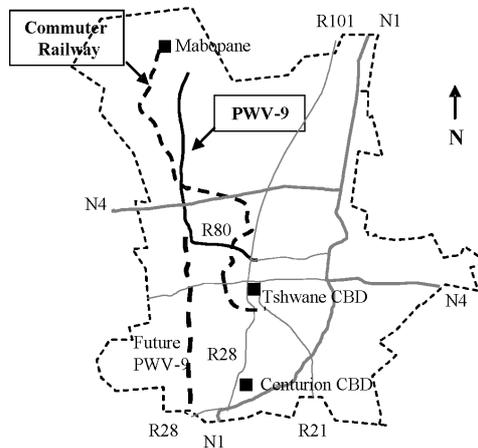
The paper is divided into the following seven sections. The first section contains the introduction to the paper. The second section provides a description of the test beds. The third section provides a description of the problem. The fourth section describes how the decision-making method was selected. The fifth section describes how the performance measures were selected. The sixth section describes the decision-making analysis. Finally, the seventh section contains the concluding remarks.

2 Description of test beds

2.1 South African corridor

The Mabopane Centurion Development Corridor (MCDC) consists of a freeway corridor (PWV-9) and a parallel commuter railway line. It runs from north to south on the western border of Tshwane (previously Pretoria). The PWV-9 freeway is approximately 40 km in length and is a divided four-lane facility with full grade separation. A 20.3 km section of the PWV-9 freeway was selected for analysis. This section stretches from Mabopane in the north to Tshwane in the south. Figure 1 shows the greater Tshwane area and the location of PWV-9 freeway.

Figure 1 Location of the PWV-9 freeway in the Houston area

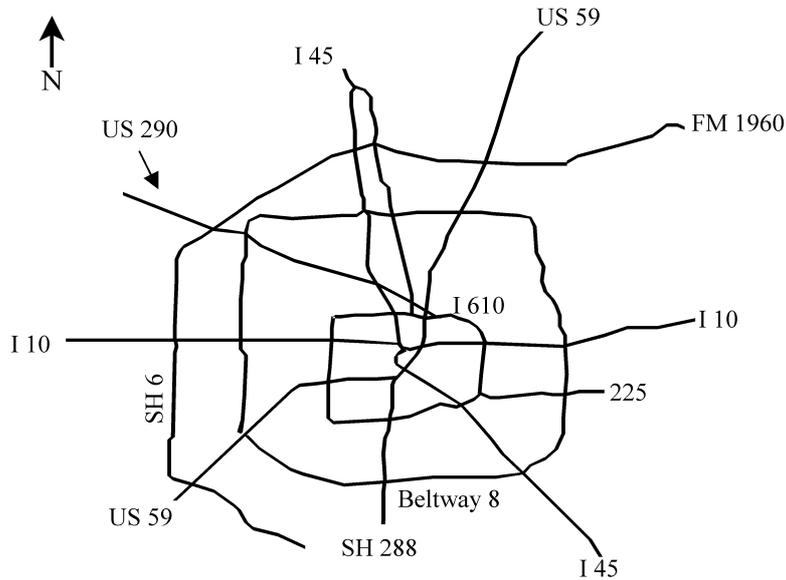


2.2 US Corridor

The US 290 corridor consists of a freeway facility (US 290) and a parallel arterial (Hempstead Highway). The US 290 freeway is a divided facility with full grade separation, three to four lanes per direction, and a High Occupancy Vehicle (HOV) lane in the median. A 23.0 km section of this freeway was chosen for this study.

The test section begins just east of FM 1960 and extends to just west of the I 610 beltway. Figure 2 shows the location of the US 290 freeway in the Houston area.

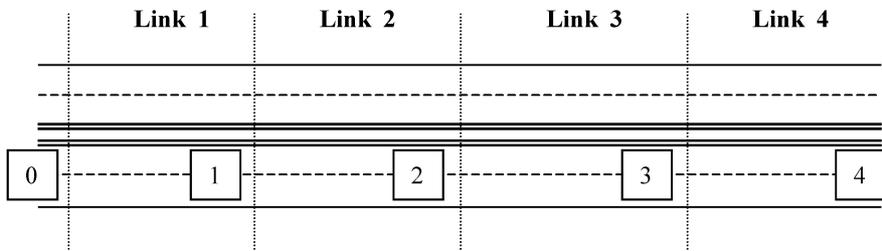
Figure 2 Location of the US 290 freeway in the Houston area



3 Defining the problem

In this example, the objective was to select appropriate sections of the US 290 and PWV-9 freeways that should be widened by one lane to optimally address the goals of sustainable transportation. The micro-simulation model used for this study made it possible to quantify performance measures at a disaggregate (link) level, which could indicate exactly which link or link combination would benefit most from widening. Road construction is typically accomplished in total sections to keep costs down. It was, therefore, decided not to consider alternatives to be made up as combinations of the various sections. For this analysis, both US 290 and PWV-9 were divided into four separate sections or links as defined by nodes zero to four. Figure 3 shows a schematic layout of the various link combinations.

Figure 3 Schematic layout of the link combinations



The construction cost for adding a lane on US-290 was assumed to be \$500,000 /km and that for PWV 9 as 2,000,000 South African rand per kilometre. The additional maintenance cost was set at \$20,000/km/year and 80,000 rand/km per year for the US-290 and PWV-9 corridors, respectively. Interest rates of 6% and 12% were assumed for the United States and South Africa corridors, respectively. The various alternatives, including the do-nothing alternative are shown in Table 1.

Table 1 Alternatives to be evaluated

<i>Alternative</i>	<i>Start and end node</i>	<i>PWV-9</i>		<i>US 290</i>	
		<i>Total length (km)</i>	<i>Construction cost (Rand million)</i>	<i>Total length (km)</i>	<i>Construction cost (\$ million)</i>
0	0-0	0	0	0	0
1	0-1	5.92	11.8	2.02	1.0
2	0-2	10.96	21.9	4.89	2.4
3	0-3	16.93	33.9	6.92	3.5
4	0-4	20.30	40.6	8.42	4.2
5	1-2	5.04	10.1	2.87	1.4
6	1-3	11.01	22.0	4.89	2.4
7	1-4	14.38	28.8	6.39	3.2
8	2-3	5.98	12.0	2.03	1.0
9	2-4	9.34	18.7	3.53	1.8
10	3-4	3.36	6.7	1.50	0.8

4 Selection of decision-making method

Conventional evaluation techniques for transportation decision-making focus primarily on the quantifiable financial and economic aspects of the investment. The public, however, is mostly concerned about sustainability issues such as social equity, safety, and the environment (Zietsman et al., 2003). A distinction can be made between evaluation techniques and evaluation processes (Meyer and Miller, 2001). An example of the former is a benefit-cost analysis, whereas the latter concerns the full spectrum of cost elements as well as interaction among the key participants in the planning process. The full spectrum of costs includes user costs, external costs, and agency costs. External costs are the ones that are most difficult to measure and include aspects such as changes in property values, noise impact, air pollution, accidents, visual intrusion, and environmental damage (Euritt et al, 1996).

Evaluation processes, therefore, are the appropriate techniques for making decisions concerning sustainable transportation systems because:

- deciding upon transportation alternatives is often more of a political process than a technical one
- the latest transportation legislation requires a great deal of inclusiveness when deciding upon transportation alternatives
- evaluation techniques do not incorporate the full spectrum of costs when evaluating transportation alternatives.

The major advantage of a multi-criteria analysis is its ability to account for a wide range of differing, yet relevant criteria. Even if these criteria cannot be expressed in monetary terms, as is the case with externalities, comparisons can still be based on relative priorities (Nijkamp and van Delft, 1977). Several methods have been developed to assess the relative importance of projects or plans based on multi-criteria analyses (Olson, 1996; Levine and Underwood, 1996; Reed et al., 1994; Richardson and Kostyniuk, 1997; Schwartz and Eichorn, 1998; Mickelson, 1998). After careful consideration, it was decided to use the MAUT approach for this study because it is a fairly simple and intuitive approach to decision making. Additionally, it allows the decision-maker to allocate relative weights to the various criteria (Mickelson, 1998).

The MAUT approach is an attempt to rigorously apply objective measurement to decision making. The basic hypothesis of MAUT is that in any decision problem, there exists a real valued function or utility (U), defined by the set of feasible alternatives that the decision-maker seeks, consciously or not, to maximise (Olson, 1996). Each alternative results in an outcome, which may have a value on a number of different dimensions. MAUT seeks to measure these values, one dimension at a time, followed by an aggregation of these values across the dimensions through a weighting procedure. The simplest and most widely used aggregation rule is to take the weighted linear average. In this case, each weight is used in conjunction with each criterion value to produce the final utilities.

The MAUT approach can be summarised into the following steps:

Step 1: Identify the various criteria and sub-criteria to be used in the evaluation process.

Step 2: Rank the different criteria and sub-criteria in order of importance.

Step 3: Rate the different criteria and sub-criteria on a scale from zero to one, while reflecting the ratio of relative importance of one criterion over the next.

Step 4: Normalise these weights on a scale from zero to one.

Step 5: Determine criteria values for each alternative by using single-attribute utility functions on linear normalised scales.

Step 6: Calculate the utilities for the alternatives by obtaining the weighted linear sum for the criteria.

Equation (1) shows how the utility values can be determined for each alternative and equation (2) shows how the normalised criteria values are determined from single-attribute utility functions on normalised scales.

$$U_j = \sum_{k=1}^{n_k} w_k n_{kj} \quad (1)$$

$$n_{kj} = f_k(s_{kj}) \quad (2)$$

where

U_j = utility of alternative j

w_k = weight of the k th criterion

n_{kj} = normalised criterion k value for alternative j

s_{kj} = value of criterion k for alternative j

$f_k(x)$ = single-attribute utility function on a normalised scale.

Equation (2) shows that single-attribute utility functions on normalised scales are used to determine values for each criterion. These utility functions can be linear or nonlinear, depending on the specific criterion.

5 Selection of performance measures

The goals of sustainable transportation can be quantified by using performance measures. These measures are geared to address the dimensions of sustainable transportation (economic development, social equity and environmental stewardship) and could differ from the conventional transportation focuses of congestion and mobility. The performance measures are therefore, based on the goals and objectives identified by the various communities for the two freeway corridors.

5.1 Tshwane corridor

The transportation-related goals and objectives identified by the communities for the Tshwane corridor can be summarised as follows (City of Tshwane Metropolitan Municipality, 2000; Houston-Galveston Area Council, 2000):

- use the provision of transportation to support economic growth
- integrate land use and transportation planning
- effectively regulate and control public transportation
- provide a safe and secure transportation system
- provide affordable mobility for all
- minimise the negative environmental effects of transportation.

5.2 Houston corridor

The transportation-related goals and objectives identified by the communities for the US-290 corridor can be summarised as follows (Houston-Galveston Area Council, 1997; Potgieter, 2001):

- provide a multi-modal transportation system
- enhance and maintain existing infrastructure
- coordinate land use and transportation development

- increase accessibility and mobility options
- protect the environment
- promote energy conservation
- promote a cost effective and affordable transportation system
- improve safety and security for the transportation system.

5.3 Selected performance measures

By carefully considering the sustainability goals for the Tshwane and Houston corridors as listed above, it becomes evident that these goals (although differently phrased) are very similar. Table 2 shows these goals in relation to the three dimensions of sustainable transportation as well as the specific performance measures that would address the various goals. An advantage of using the same performance measures is that the corridors can be compared at the level of performance measures as well. It should be noted however that the proposed procedure of this paper can just as easily be applied to totally different sets of goals resulting in different performance measures.

Table 2 Selected sustainability goals and performance measures

<i>Sustainability dimension</i>	<i>Goals</i>	<i>Performance measures</i>
Social	Maximise mobility	Travel rate
	Maximise safety	Accidents per VMT
Economic	Maximise affordability	Point-to-point travel cost
Environmental	Minimise air pollution	Volatile Organic Compounds (VOC), Carbon Monoxide (CO), and Oxides of Nitrogen (NOx) emissions
	Minimise energy use	Fuel consumption

As shown in Table 2, each criterion is represented by one or more performance measures. Mobility is represented by travel rate, safety by the five categories of accident severity, affordability by point-to-point travel cost, air pollution by three pollutant types, and energy-use by fuel consumption. It should be noted that travel rate is the rate of motion expressed in minutes per kilometre.

6 Decision-making analysis

6.1 Criteria weights

The use of criteria weights is a controversial issue because it opens up the analysis to a certain amount of subjectivity. It could, however, serve as an important tool to allocate the relative importance of the various criteria, as they are perceived, by the decision makers. For illustration purposes, researchers followed a dual approach for this research, one that includes criteria weights and one without criteria weights. In the un-weighted case it is assumed that all the criteria are equally important and the analysis is free from subjectivity.

Typically, the criteria weights are derived through an interactive process with the decision-makers. For this research, the weights for the overall performance measures were based on discussions with representatives from the city of Tshwane and the Greater Houston-Galveston Area Council. The weights for the individual criteria were developed through a Delphi process using four experts in the field of transportation planning.

The total weight of the performance measures representing the individual criteria had to sum up to one so the criteria are not weighted twice. The weights of the individual performance measures are based on the relative costs to society for those measures. For example, in the case of emissions, the weights were determined on the basis of the cost of controlling the three major vehicular pollutants (VOC, CO, and NO_x) (Wang et al., 1994). Traffic accident costs include death, injury, disability, lost of productivity, and material damage (Litman, 2005). Table 3 shows the criteria selected for this analysis as well as the performance measures selected to represent the individual criteria. The table additionally shows the weights allocated to the criteria and their respective performance measures.

Table 3 Criteria and performance measurement weights

<i>Criteria</i>	<i>Weight</i>	<i>Performance measure</i>	<i>Weights</i>
Mobility	0.30	Travel rate	1.000
		Fatal	0.916
		Incapacitating	0.063
Safety	0.20	Non-incapacitating	0.013
		Possible injury	0.007
		Damage only	0.001
Affordability	0.20	Travel cost	1.000
		VOC emissions	0.430
Air pollution	0.15	CO emissions	0.120
		NO _x emissions	0.450
Energy use	0.15	Fuel consumption	1.000

6.2 Criteria values

The CORSIM micro simulation model was used to model the traffic flow characteristics such as volume, speed, and travel time for the AM peak hour. Researchers used a per-kilometre basis to quantify performance measures for each of the links of the three test corridors. The values for the various performance measures were then calculated as follows:

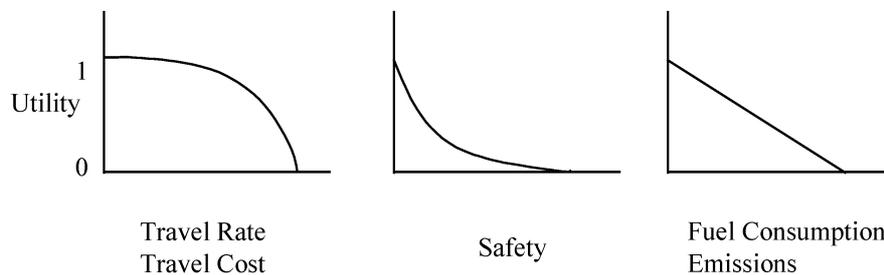
- Travel rate is the rate of motion in minutes per kilometre, for a specified roadway segment and is calculated by dividing the segment travel time by the segment length. Travel rate was determined from the individual travel time information.
- Accident rate is defined as the number of accidents per vehicle miles of travel. It was determined from accident data and volume information.

- Fuel consumption was determined with a widely used energy-based instantaneous model (IM) developed by Biggs and Akcelic (1986) and National Research Council, (2000)).
- Emissions were determined for three pollutants, VOC, CO, and NOx. The MOBILE6 emissions model was used to determine the necessary emission rates.
- Travel cost was based on the total cost associated with travel time, fuel consumption, emissions, maintenance and tires, and safety.

The values of the quantified performance measures (criteria values) were normalised for comparison purposes. The normalised criteria values were determined by using a single-attribute utility function on a normalised scale. The normalised scale ranges from zero (worst performance) to one (the best performance). Normalisation was used because the different performance measures have different units of measurement. Three different shapes – linear, concave, and convex – were used to reflect the driver’s and/or planning organisation’s perception concerning the different performance measures. The equation for the single-attribute utility functions is shown in equation (3). Figure 4 shows the shapes of the utility functions for the various performance measures.

$$\begin{aligned}
 U(x) &= a + bx \text{ when } c = 0, \text{ (straightline)} \\
 U(x) &= a + be^{(-cx)} \text{ when } c \neq 0, \text{ (parabola).}
 \end{aligned}
 \tag{3}$$

Figure 4 Shapes of utility functions



6.3 Calculating utility values

There were three applications used to illustrate their effects on the final decision. The first application uses a pure NPW analysis. The other two techniques were based on the MAUT approach, one including criteria weights and the other excluding criteria weights. The sustainability performance measures used in the MAUT approach include fuel consumption, emissions, travel rate, and safety. It should be noted that the change in accidents as a result of the various alternatives was based on the change in VMT between the do-nothing alternative and the one under analysis. The calculation of the NPW is shown as equation 4, whereas that of the MAUT approach was shown as equations (1) and (2).

$$NPW_j = T_j - (C_j + M_j)
 \tag{4}$$

where

NPW_j = net present worth for alternative j

U_j = utility of alternative j

T_j = present value for time savings for alternative j

C_j = present value of construction cost for alternative j

M_j = present value of maintenance cost for alternative j .

The results are also shown graphically in Figures 5 and 6 for the PWV-9 and US 290 corridors, respectively.

Figure 5 Normalised utility values on PWV-9

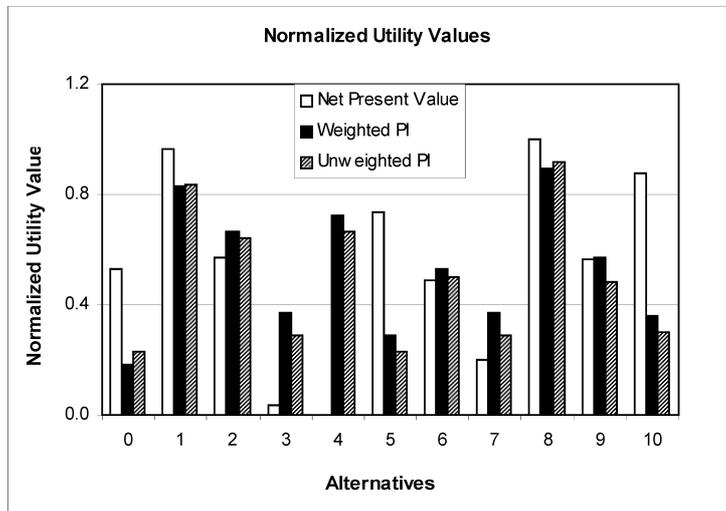
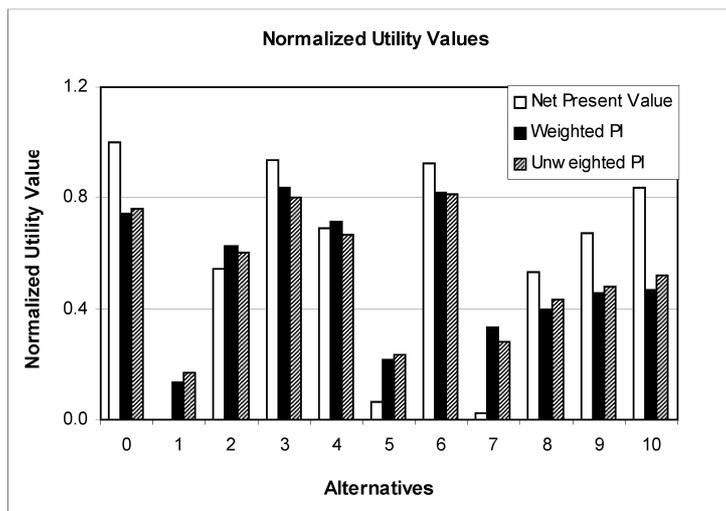


Figure 6 Normalised utility values on US 290



Figures 5 and 6 show that there are a wide range of utility values for the various alternatives and applications. Under all three approaches, alternative eight is the best project for the PWV-9 corridor. The projects faring second and third best, however, differ between the NPW and MAUT approaches, although the weighted and un-weighted MAUT approaches produced the same second and third alternatives. For the US 290 corridor, the same three projects were listed as the top three alternatives for both the NPW and MAUT approaches. The order of these projects, however, differs from approach to approach.

These figures also show that the two MAUT approaches produce similar results, whereas the results based on the NPW approach are quite different. The analyses, therefore, illustrate that the type of decision-making methodology, and particularly whether the sustainability effects are included, have a direct effect on the final decision. The MAUT approach made it possible to include a broad range of sustainability issues. The decision-maker, however, still must choose how to allocate the available funding.

7 Concluding remarks

This paper provides a description of how decisions concerning transportation programmes and projects can be made in the context of sustainable transportation. It provides information on identifying appropriate performance measures for sustainable transportation. The identified performance measures were then quantified with a traffic simulation model (CORSIM) as well as transportation environmental models. The quantified performance measures were then used in three decision-making methodologies to test their effect on the final decision. The test bed used for this study comprised a transportation corridor in Tshwane, South Africa and one in Houston, Texas. The following specific findings were made in this study:

- Performance measures could be identified that addressed the goals and objectives of the two corridors within the three dimensions of sustainable transportation.
- It was shown how these performance measures could be quantified at a disaggregate (link) level by using a micro simulation model and various environmental models.
- The quantified performance measures were then used with the NPW and the weighted and un-weighted MAUT approaches to make decisions regarding transportation improvements. Criteria weights are optional and are used to distinguish between the relative importances of the various criteria.
- The MAUT approach was found to be most conducive to make transportation decisions within the context of sustainable transportation because it made it possible to include a broad range of quantitative and qualitative sustainability issues in the decision-making process.
- The disaggregate approach proposed in this paper makes it possible to isolate individual links within a corridor that should be widened.
- The methodology proposed in this paper can be applied irrespective of the goals of the corridors.

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