

# Economic analysis of bicycle tracks using the HDM-4 model - case study for São Paulo city

## *Análise de benefícios econômicos de ciclovias usando o modelo HDM-4 - estudo de caso para o município de São Paulo*

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**ABSTRACT**

In addition to technical studies, bicycle paths should be a product of planning and investment policies considering the ability of projects to generate socioeconomic benefits, implementing policies' objective analysis relevant to the feasibility of projects for the implementation of exclusive bike tracks. In this paper the Non-Motorized Traffic (NTM) model of the HDM-4 (Highway Development and Management) software is applied for the analysis of different alternatives for bicycle lanes, evaluating aspects such as current and potential cyclists demand, operation speed, capital costs and economic profile of bicycle users. The combination of such variables leads to technical and economic alternatives whose analysis results relevant differences in their profitability indicators. The analyses were carried out considering two scenarios; the first comprises the analysis of the profitability of alternatives structured with normative guidelines that, in terms of speed, represent ideal operating conditions; the second scenario consists of a more realistic evaluation for the city of São Paulo, considering speed restrictions and diversifying the user profile according to the per capita income of the main regions of the city. The results reflect interregional diversity about the desirability of bikeway projects based solely on the monetary benefits of reduced travel times. The kern results point out financial risk of the projects as governed by speed and traffic, also requiring a demand of over 1000 bicycles/day and an operation that exceeds 8 km/h to support bicycle projects investments.

**RESUMO**

Além dos estudos técnicos, as ciclovias devem ser produto de políticas de planejamento e investimento considerando a capacidade dos projetos de gerar benefícios socioeconômicos, implementando análises objetivas de políticas relevantes para a viabilidade de projetos de implantação de ciclovias exclusivas. Neste artigo o modelo de Tráfego Não Motorizado (NTM) do software HDM-4 (Highway Development and Management Model 4) é aplicado para a análise de diferentes alternativas de ciclovias, avaliando aspectos como a demanda atual e potencial de ciclistas, a velocidade de operação, custos de capital e perfil econômico dos usuários de bicicletas. A combinação dessas variáveis leva a alternativas técnicas e econômicas cuja análise resulta em diferenças relevantes em seus indicadores de rentabilidade. As análises foram realizadas considerando dois cenários; o primeiro compreende a análise da rentabilidade de alternativas estruturadas com diretrizes normativas que, em termos de agilidade, representam condições ideais de operação; o segundo cenário consiste em uma avaliação mais realista para a cidade de São Paulo, considerando restrições de velocidade e diversificando o perfil do usuário de acordo com a renda per capita das principais regiões da cidade. Os resultados refletem a diversidade inter-regional sobre a conveniência de projetos de ciclovias com base apenas nos benefícios monetários de tempos de viagem reduzidos.



## 1. INTRODUCTION

Road infrastructure, like any other type of infrastructure, is immersed within a planning cycle that begins with the idea of investment and ends with the completion or abandonment of a project for some reason associated with a specific technical or socioeconomic criterion.

Socioeconomic evaluations must compile all the variables and technical studies of a project; therefore, only when feasibility is determined within the economic and social context of the region, it becomes plausible to state that projects of public agencies go through all the planning stages, regardless of the economic indicators obtained.

In Brazil, highway infrastructure projects meet well-defined guidelines and methodologies to assess their technical feasibility, as well as to establish levels of service appropriate according to demand. However, in the public planning and investment sector, there is still a gap in the treatment of bicycle infrastructure projects, and it is a common practice to disregard the costs and benefits of non-motorized vehicle users.

Altering such conventional perspective, in this paper it was performed a technical and economic analysis of different situations of bicycle tracks projects in the city of Sao Paulo, which allows the identification of investment levels, socially viable, according to the cyclists' demand and other variables inherent to the projects.

The methodological approach of this work is based on the analysis of different alternatives for bicycle projects using the non-motorized traffic (NMT) model of the Highway Development and Management (HDM-4) software, evaluating factors such as current and potential cyclists demand, operation speed, capital costs and users economic profile.

Thus, this study seeks to collaborate in the *status quo* of socio-economic studies by employing tools that can contribute to manage policies and optimization of public money, facilitating decision making process in bicycle projects within urban roadways in São Paulo city, considering that in recent years the expansion of the city's bicycle network is vertiginous, in contrast to the status of methodologies to assess the technical feasibility of bicycle infrastructure.

## 2. BACKGROUND

According to the Inter-American Development Bank (IDB, 2015), there are three types of cycling infrastructure: green or independent, consisting of lanes for the exclusive use of bicycles; segregated, which corresponds to lanes demarcated by paint or other type of separator depending on the speed of motorized traffic; and shared, which is an open way to other traffic modes, since the operating conditions allow more than one transport mode. According to Brazilian guidelines, the nomenclature of the cycling infrastructure mentioned correspond to bike track, bike lane and shared lane, respectively.

The classification of bicycling infrastructures, according to its level of segregation, is determinant in the cost of implementation and maintenance works, therefore, bike tracks are the most expensive investment within the three options mentioned above, being a scarce infrastructure in São Paulo's network. As published by São Paulo Traffic Engineering Company (CET, 2021), the city's bicycle network has 684 km, of which only 154.3 km are bicycle tracks, 32.1 km are shared lanes, and the remaining 497.6 km are bicycle lanes.

In terms of planning, São Paulo has the Bicycle Paths Plan 2019-2028 (CET, 2020), released and discussed in 10 workshops that took place between years 2018 and 2019.

Compared to previous plans, its goals are ambitious, aiming to reach 1,800 km of network during the period between 2021 and 2028. The Bicycle Plan, still being in process of implementation, brings together elements of *PlanMob* (2015) and requests from civil society, prioritizing network connectivity and efficiency.

With regard to legislation and rules for the cycling sector, a relevant change is attributed to Municipal Law No. 16.738 of November 7, 2017, whose Article 4 states: "*The implementation of bikeways should be preceded by public hearings and the presentation of demand, feasibility, and road impact studies, which should be fully disclosed on the website*" (SÃO PAULO CITY HALL, 2017).

The law has generated concern among organizations promoting bicycle use such as *Vá de Bike* and *Ciclocidade*. The apprehension to the law by cycloactivists is sustained in that bicycle infrastructure projects do not have enough demand to make the investment viable, due to the fact that bicycle trips are mainly generated and attracted after the construction of the bikeways (BASILIO, 2017), what at least suggests an existing repressed demand.

However, the realities described are not enough to disapprove the practice of feasibility studies in bikeways projects, especially considering that traffic generated, or potential demand are determining variables in socioeconomic analysis methodologies.

## **2.1. Non-Motorized Traffic (NMT) in the Highway Development and Management Tool (HDM-4)**

The HDM-4 software, developed to technically and financially evaluate the initiatives of public and private agencies that manage road networks, quantifies the profitability of strategies, programs, or individual projects by weighing the benefits in terms of decreased vehicle operating costs (VOC) and travel time savings.

In this study the tool so-called *project* within the software was employed, since the segregation of Non-Motorized Traffic (NMT) is typified as a work to improve the existing infrastructure that changes the operating conditions of the different traffic modes. NMT is considered as a passenger and freight transport mode and not only as a noise factor for motor vehicles (KERALI et al., 2000). Thus, in HDM-4 the costs and benefits of NMT are calculated separately for four types of vehicles: pedestrians, bicycles, carts, and cycle-rickshaws.

Gradually, both pedestrians and Non-Motorized Vehicle (NMV) users have gained space in socioeconomic feasibility analyses of projects of different types. The subject was addressed by the World Bank through the study developed by PADECO (1996) which had as object the inclusion of the NMT module in HDM-4, based on the concepts of Hoban (1987) that had already been applied in field studies in Indonesia to determine the effect on operating speed caused by the conflict between motorized and non-motorized vehicles.

Kerali et. al (2000) revised the NMT model in order to establish the final specifications to be adopted; as a result, changes were made regarding the effects of rolling resistance on the speed of non-motorized vehicles.

The NMT models were incorporated into the pre-existing models for Motorized Traffic (MT) on highways, whose operation is considered uninterrupted and adequate to develop constant speeds. Nevertheless, it is a reality that NMT comes from metropolitan areas, industrial or commercial agglomerations, which suggest the presence of urban settlements adjacent to the highways, and without them, the incorporation of this module in the software would have been

unfeasible or unnecessary. Theoretically, NMT travel on the shoulder of the highway or, in the worst case, share lanes with motor vehicles; this interaction generates an impact on the travel times of the entire fleet that is quantified by the HDM-4 software models.

The purpose and characteristics of the models may prematurely discredit the HDM-4 software as a tool for analyzing NMT on urban roadways; however, the assumptions of the models constitute the technical foundation of some studies that are characterized by having taken advantage of the software's potential beyond its limitations.

Kumar (2012), Chopra *et al.* (2017) and Yogesh *et al.* (2014) have developed different studies in India on the use or adaptation of the HDM-4 software on urban roads by means of strategic modeling to prioritize investments. In Bogota (Colombia), the *Instituto de Desarrollo Urbano* (IDU, 2009), calibrated the road deterioration and user cost models of HDM-4 for the management of the city's road network, restricting speed by means of a reduction factor capable of expressing numerically the effects of congestion and traffic disruptions. In Brazil, Gueller (2012) compared the model developed by Tavakoli *et al.* (1992), proper management in urban roads of medium-sized cities, with modeling in HDM-4 software.

The studies showed satisfactory results, especially for defining a schedule for ways rehabilitation or maintenance interventions, which depends on the Road Deterioration (RD) and Road Works Effects (RWE) models.

In HDM-4 the interaction between TM and NMT depends crucially on the existence and size of the shoulder on the road. By making an analogy with urban roads, the level of interaction between vehicular traffic and bicycle traffic is governed by the type of bicycle infrastructure.

In this case, shared lane, bike lane, and cycle tracks differentiate the interaction depending on the level of segregation, and it is possible to say that shared lane are infrastructures of high contact between both types of users, on bike lanes interaction decreases according to the separation technique (paint or retroreflective tacks), and on bike tracks there is no interaction between traffic modes for most of the route. However, even under the best segregation conditions, several impedance factors persist, such as intersections, pedestrian interference, internal conflict between cyclists, bikeway capacity, among others, which reduce the operating speed and, consequently, affect the socioeconomic efficiency of the infrastructure.

Bennett and Greenwood (2000), in the software manuals point out that the mutually generated effects between the TM and NMT models are controlled and defined through speed reduction factors. The speed of motorized traffic can be reduced due to the presence of non-motorized traffic by means of impedance factor  $X_{NMT}$ , and reciprocally the speed of non-motorized traffic is reduced by means of the factor  $X_{MT}$ . The model limits the value of the  $X_{MT}$  factor between 0.4 and 1, where values close to or equal to 1 tend to cancel out the conflict and values close to 0.4 are employed to add model impedance and represent critical operating conditions.

In this study it is assumed null the change in motorized vehicle speed by the implementation of the bikeway, so the effects on its operating costs are not evaluated. This assumption is based on the difficulty of isolating side friction effects due exclusively to the presence of bicycles on urban roads in the area of influence of a bicycle path project.

The main equations of the software models correspond to the operating speed, which is given by:

$$V = X_{MT} \max[0, 5, \min(V_{DESIR}, V_{ROUGH}, V_{GRAD})] \quad (1)$$

*V*: Operating speed (km/h).

*VGRAD*: Speed limited by the slope of the track (km/h).

*VDESIR*: Desired speed by vehicle type and surface type (km/h).

*VROUGH*: Speed limited by the surface irregularity (km/h).

*XMT*: Reduction factor due to motorized traffic and activities adjacent to the track.

The variables in equation (1) are described as follows:

$$VROUGH = VDES + a_0 RI \tag{1}$$

$$VGRAD = VDES + a_1 GR \tag{2}$$

*VDES*: Desired speed (km/h).

*a*<sub>0</sub>: Model coefficient associated to the irregularity.

*a*<sub>1</sub>: Coefficient of the model associated to the slope.

*RI*: Irregularity of the road.

*GR*: Coefficient of the bicycle type vehicle associated with the grade of the road, predetermined in the model (-0.04).

However, the speed as a function of geometry depends on the slope the cyclist experiences, being higher when downhill and with some restriction when uphill, thus:

$$VGRAD = \max[0,14, \min(VDES + a_1 GR)] \tag{3}$$

*GR*: Coefficient of the bicycle vehicle associated with the grade of the road for uphill (+) or downhill (-) travel:

$$GR = \pm \frac{RF}{1000} \tag{4}$$

*RF* being the number of descents and ascents per kilometer that is entered into the geometry module as a track characteristic.

Equations (2), (3) and (4) contain calibration coefficients or factors, which were defined by Odoki and Kerali (2005) during model refinement and their values are shown in Table 1.

**Table 1** – Default values of the speed model for VNM - bicycle

	VDES on Paved roads	VDES on unpaved roads	Roughness	Slope
Non-motorized vehicle type	km/h	km/h	<i>a</i> <sub>0</sub>	<i>a</i> <sub>1</sub>
Bicycle	21,3	18	-0,225	-28

### 3. STUDY METHODOLOGY

The socioeconomic analysis in this study consists of two scenarios. The first scenario comprises the analysis of the profitability of different project alternatives structured with guidelines recommended by manuals or reference documents that, in terms of speed, represent ideal operating conditions. This scenario considers socio-economic characteristics of cyclists that already use bicycle infrastructure; however, it does not represent the diverse socioeconomic conditions of potential users located in other regions in São Paulo city, which do not have expressive development of bicycle infrastructure. The second scenario, on the other hand, consists of a more realistic assessment considering lower operating speeds associated with restrictions such as high slopes, interruptions, space limitations for implementation, conflicts with pedestrians, among other impedance factors. In addition, the second scenario evaluates the diversification of the user profile by analyzing up to six income levels that represent the average per capita of the main regions of the municipality of São Paulo.

### 3.1. Variables Selection

The analysis is based on a combination of explanatory variables that meet the prerequisite of being defined as input data in the HDM-4 model and that are available in studies and documents with broad technical potential to be used, such as: speed, traffic, and pavement typology

#### 3.1.1. Traffic

There are numerous demand scenarios that may represent in the bicycle network of a metropolis, therefore, in order to properly represent the bicycle demand in the city, 30 counting stations from Association of Urban Cyclists of São Paulo – (Ciclocidade, 2018) and 34 stations from CET (2019) were analyzed; all information was included in the analysis by calculating measures of central tendency (mean and median) and measures of position (first and third quartile) represented by the box-and-whisker plots (Figure 1). The extremes of the box indicate the degree of dispersion of the data and the size of the central box identifies where the 50% of the sample values are located, which in turn provide the most probable values to incorporate in the analysis.

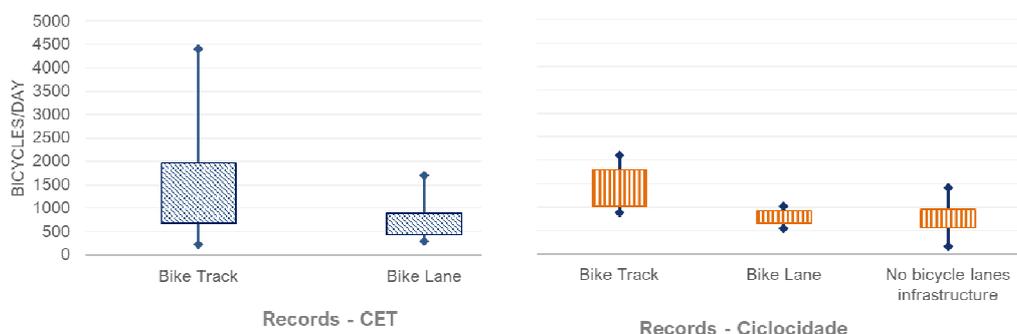


Figure 1. Traffic variable distribution

Comparison of the two data sources disclosed similarities in central tendency and position values. Bike tracks have an average traffic that varies between 1,469 and 1,564 bicycles per day, according to Ciclocidade and CET respectively. The bike lanes have lower average demands, with values around 710 and 786 bicycles per day. In fact, the third quartile shows that 75% of the bike tracks have a traffic equal or inferior to 1,970 bicycles/day, while in the bike lanes the demand is reduced to 908 bicycles/day.

Thus, to ensure coverage of the main demands analyzed, it was adopted as a baseline value for socioeconomic analysis a traffic of 500 bicycles per day, increasing gradually up to 2,000 bicycles per day. The higher demands were included in the analysis through the generated traffic, which was defined through similar statistical analyses, considering the percentage increment of demand in the first years of bikeways implementation. However, the prominent amplitude of the data set required the evaluation of a wide range of values integrated by the percentages of 10%, 20%, 30%, 40%, 50%, 100% and 150%. The last two values are included to represent success stories such as the Faria Lima Avenue bike track, which in 2019 reached values above 6,000 bikes/day and managed to double demand in the first years of operation.

In summary, the socioeconomic analyses were performed for six demands corresponding to 500, 750, 1,000, 1,250, 1,500 and 2,000 bicycles per day and each of these values was increased and analyzed with the set of percentages defined for the generated traffic.

### 3.1.1.1. Traffic growth rates

According to *METRÔ* (2019), between 2007 and 2017 there was an increase of 0.1 million bicycle trips, for which, the development of bicycle infrastructure and the implementation of bike share programs were instrumental. In this context, the linear growth rate of demand corresponds to 3.33% (has been approximated to 3%). However, since this is a study that seeks to measure the sensitivity of mutable and exogenous variables such as traffic, it is considered appropriate to evaluate other rates that represent an optimistic (6%) and pessimistic scenario (0% - no growth).

### 3.1.2. Pavement types - capital and maintenance costs

Krizek et al (2006) state the design of bikeways, which depends on several variables that are specific to the location, can affect not only the functional life of the bicycle path, but also its economic life.

Bicycle reference guides such as American manual (AASHTO, 2013) and the Dutch manual (CROW, 2011) do not standardize pavement structures, leaving the technical decision subject to the support conditions of each site; however, both guidelines emphasize the importance of considering the possible overloads that request bikeways, such as maintenance vehicles or infringing vehicles.

The pavement was included by varying the thicknesses of different structures: Asphalt Concrete (AC) with thicknesses of 20 mm, 30 mm and 40 mm, Porous or permeable Friction Courses (PFC) of 40 mm, Double Surface Treatment (DST) and 100 mm non-dowelled plain Concrete (C), and for all cases a 100 mm granular underneath base; subgrade reinforcement varied between 0, 150 and 400 mm.

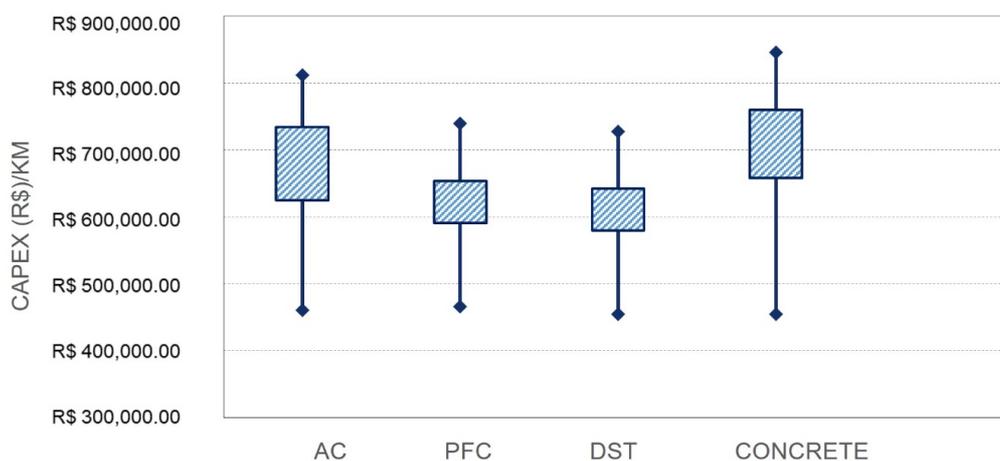


Figure 2. Distribution of Capex/km by pavement type

Since the NMT model of HDM-4 does not present any distinction in structural terms, this variable becomes exclusively economic and is represented by the project *Capital Expenditure* (CapEx). For this purpose, it was considered a 2.5 m wide platform called a fully segregated bikeway on clean terrain as recommended by the Brazilian Ministry of Cities (2007). The cost preparation corresponds to the construction of 1 km of track with support platform - cut or embankment, pavement structure, drainage works, horizontal and vertical signs and safety devices, as well as the factor of Benefits and Indirect Expenses (from Portuguese, “BDI”).

The unit prices were adopted from official and governmental databases. In order to establish representative values for bikeways investments, the data were diagrammed as shown in Figure 2.

In order to represent different investment possibilities and to simplify the economic scenarios, after a previous analysis of different bicycle infrastructure cost, it was opted to analyze a range of capital costs that oscillate between R\$400,000 and R\$1,100,000. Since HDM-4 does not have deterioration models that express the effects of maintenance, in this study it was proposed to program global costs for periodic and routine maintenance, both functional and structural. The annual maintenance of the bicycle track amounts to approximately R\$20,000 per kilometer with slight differences depending on the type of road surface; the figure is consistent with the reference costs of the National Planning Department (DNP) of Colombia (2017), which gathers experiences of consolidated networks such as the Bogotá bikeways system.

### 3.1.3. Speed (S)

Bikeway projects must satisfy the primary requirement of providing as direct a route as possible, and all factors affecting travel time, such as speed, traffic flows, delays, and detours, must be evaluated. In this study, the impedance is expressed numerically by the XMT factor which, under specific model conditions, reduces the design speed until the selected operating speeds are obtained as discrete values to integrate the factorial of project alternatives.

In the normative scenario, a design speed of 30 km/h is adopted as recommended by the global organization Institute for Transportation and Development Policy (ITDP, 2017), as well as other international guidelines such as IDU (1999), CROWN (2011), AASHTO (2012), DPTI (2015), while the operating speed is set with systematic reductions through the XMT iteration. In the regional scenario, the selected speeds are more critical and correspond to the results of the research analysis of the Association of Urban Cyclists of São Paulo – *Transporte Ativo* and *Ciclocidade* (2016), from the selected operating speeds, and the XMT factor and design speed are iterated.

**Table 2 – Speed Data**

Scenario I - Normative Context				Scenario II - Regional			
Base	Alternative	Desired	Operating	Base	Alternative	Desired	Operating
Speed	Speed	Speed	Speed	Speed	Speed	Speed	Speed
(km/h)	(km/h)	XMT	(km/h)	(km/h)	(km/h)	XMT	(km/h)
		0,55	15			0,52	8
		0,73	20			0,65	10
10 km/h	30km/h	0,91	25	5	18	0,98	15
			5				3
			10				5
			15				10

It should be noted that the factor that governs the model results is not directly associated with the operating speed, but rather with the user's speed gain. Thus, the benefits in the normative context in terms of speed are higher when operations above 20km/h are evaluated. Table 1 presents the XMT factors, design and operating speeds and speed gains for each of the scenarios evaluated.

Another factor that regulates the speed in the HDM-4 model is the surface roughness in terms of IRI (International Roughness Index), which increases gradually depending on an environmental coefficient (selected by default). In this study an initial IRI of 3 m/km is used and after 20 years it reaches a value of 5,6 m/km.

The roughness model increases gradually as a function of weather conditions. It is worth noting that, to roads, in HDM-4 the rate of deterioration of roughness is conditioned to the sum of other degradations, such as loss of structural capacity, cracks, wear, potholes, among others, which are strictly associated with traffic loads. In the non-motorized traffic models, traffic loads are not considered, so degradations do not impact the irregularity and the IRI value is only affected by the weather factor predetermined in the software according to Table 1. In conclusion, for non-motorized traffic paths, the software simplifies the roughness model and provides a factor that increases the user's impedance conditions.

### 3.2. Vector Space Size

Since the sampling is being performed in 3 sampling variables, there are several possibilities of *sampling vectors*, i.e., each bikeway section can receive a discrete value of each sampling variable, as shown in the following equation:

$$Cycle\ track_i \in \begin{bmatrix} Traffic\ level_j \\ Speed_k \\ Pavement\ Cost_l \end{bmatrix} \tag{5}$$

In other words, the i-th bicycle track can belong to the j-th traffic category, have a k-th operating speed, and have an associated with a l-th pavement cost. With these variables it was performed a joint-distribution analysis (more commonly known as crosstab analysis).

**Table 3 – Project alternatives variables**

Scenario	Traffic		Speed			Pavement
	Normal Traffic Base Alternative	Generate Traffic With Project (%)	Desired Speed (km/h)	Speed Operating Base Alternative (km/h)	Speed Operating With Project (km/h)	Capex (R\$/km)
I. Normative Context		10				400,000
	500	20				500,000
	750	30				600,000
	1,000	40				700,000
	1,250	50			15	800,000
	1,500	100			20	900,000
	2,000	150	30	10	25	1,000,000
II. Regional		10				400,000
		20				500,000
		30				600,000
	500	40				700,000
	750	50			8	800,000
	1,000	100			10	900,000
		150	15	5	15	1,000,000

In addition to the base alternative, each section is evaluated in 168 different situations, which correspond to the combination of 7 possibilities of generated traffic, 8 investment values for build works and 3 operation speeds. Each combination corresponds to a project alternative, therefore, there are 1008 different combinations or vector possibilities for the normative scenario.

In the regional scenario it was considered pertinent to limit the demand according to the statistical analyses carried out, being possible to reach values of up to 2500 bicycles/day in the first years of operation service when incorporating the maximum percentage of generated traffic. The evaluation by regions implies performing six times the modeling of each of the

projects with the described combinations, since the user's average income is inserted in the software configuration. For each of the scenarios evaluated (normative and regional), the variables for the factorial of the project alternatives are presented in Table 2 and inserted into the HDM-4 as shown in Figure 3.

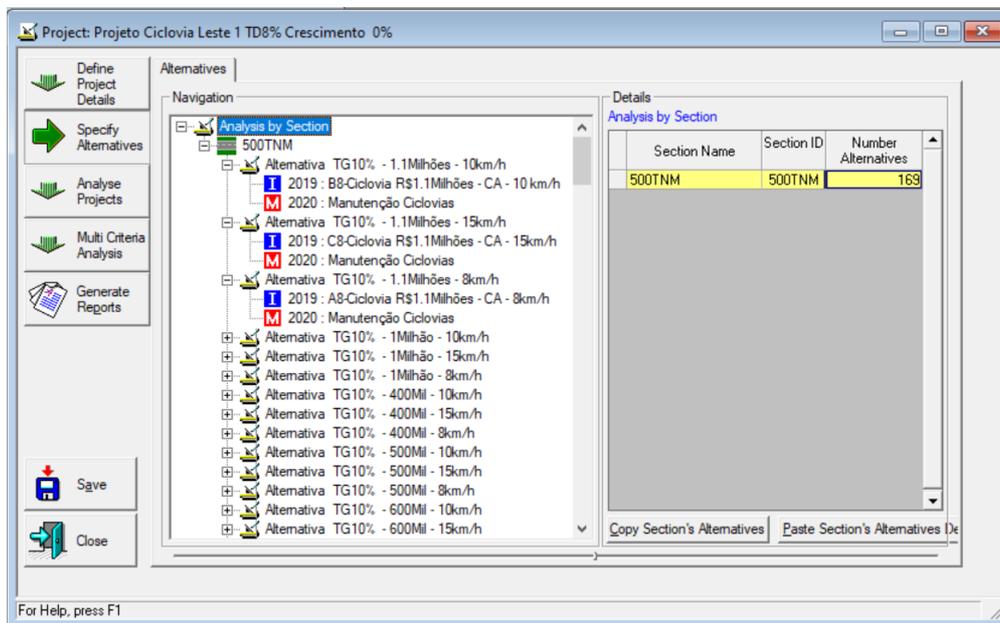


Figure 3. Project Alternatives in HDM-4 (after crosstab)

### 3.3. Socioeconomic Analysis

#### 3.3.1. Configuration and parameterization

The HDM-4 can be configured for local conditions in order to reflect the reality of the case to be studied. In this research, the configuration consists in the insertion of variables of interest that represent factors such as climate, geometry and currency type.

The parameterization of the system involves the values concerning the physical and economic characteristics of the fleet and, with greater relevance, includes the passenger time value which, in this research, is represented by the user's income, a factor that according to Brilhante (2012), determines the ownership of vehicles and impacts on the individual choice of transport mode.

Two analyses were developed to represent with figures the cyclist's economic profile. The first evaluation consisted in considering income values from the research on cyclist profile whose sample corresponds to 1800 cyclists that, naturally, already use the city's bikeways and was conducted by *Ciclocidade* and *Transporte Ativo* (2016), members of the Association of Urban Cyclists of São Paulo. The second analysis focuses on the diversity of the inter-regional per capita income in the city of São Paulo, being applicable, for instance, for mobility and regional development projects when the demand is still repressed, and the target user is difficult to identify. According to the São Paulo State Data Analysis System Foundation (SEADE, 2020), in terms of per capita income, São Paulo has a wide diversity, considering five main regions as shown in Figure 4 (North, South, East 1, East 2 and Expanded Center). A sixth income category was included aiming at representing regions with critical social conditions (favela), which have a high Social Vulnerability Index (from Portuguese, "IPVS").

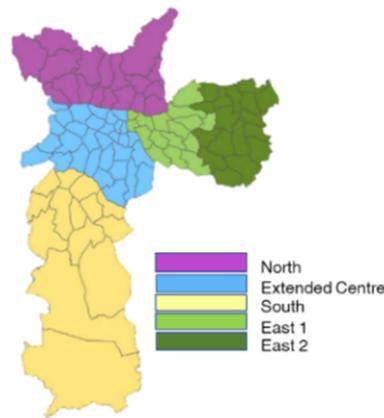


Figure 4. São Paulo regions - per capita income (SEADE)

Finally, the value of passenger time in R\$/hour was calculated considering the divisor of 220 monthly hours, which includes the remunerated weekly rest period, besides being widely accepted and used in the Brazilian labor regime.

Table 4 – Average per capita income per region

Region	Average per capita income by Region - Source SEADE		Average per capita income for users - Source Ciclocidade and Transporte Ativo	
	Average monthly income (R\$)	Average Income per Hour (R\$)	Average monthly income (R\$)	Average Income per Hour (R\$)
North	1,344	6.10		
South	1,095	5.00		
East 1	1,439	6.50	2,669	9.10
East 2	992	4,50		
Extended Centre	2,366	10.80		
High IPVS condition	13.47 per day	1.70		

Table 5 – Parameters of Non-Motorized Model of HDM-4

Category	Description	ID HDM-4	Unit	Adopted parameter	Default parameter
Basic Characteristics	Wheels Type	-	-	Pneumatic	Pneumatic
	No of Wheels	NUM_WHEELS	un	2	2
	Wheels Diameter	WHEEL_DIA	m	0.7	0.7
	Weight	WGT_OPER	kg	100	100
	Payload	PAYLD	kg	10	30
	Average life	LIFE0	years	7	10
	Working Hours	HRWKO	h/year	166	150
	Annual km	AKMO	km/year	2,113	2,500
	Passengers	PAX	unit	1	1
Unit Costs	Purchase Cost				
	According to ABRACICLO (2018)	PCHCk	R\$	791.88	-
	Crew Wages		R\$/Hr	-	-
				9.10	
				I. Normative Context	
				see Table 3 II. Regional Scenario	
	Passenger Time Value	PAXVk	R\$/Hr		
	Cargo Holding Time	CARGCk	R\$/Hr	-	-
	Annual Interest				
	Average rate according to BCB (2019)	INTCk	%	5.5	-

Table 5 summarizes the values defined to parameterize the aspects related to the user and the type of vehicle and presents a comparison with the parameters predetermined by Odoki and Kerali (2005) in relation to the vehicle characteristics.

### 3.3.2 Conditions of the Socioeconomic Analysis

The horizon adopted for this analysis corresponds to 20 years, a period that is in consonance with the long useful life that bicycle paths can offer under adequate maintenance conditions, and the analysis period is consistent with Australian guidelines given by Department of Planning Transport and Infrastructure (DPTI, 2015), which adopts 20 years for bicycle paths with flexible surfaces.

Regarding the Social Discount Rate (SDR), this study uses the value of 8.5% recommended by the Ministry of Economy of Brazil (2020) for cost-benefit analyses of infrastructure investment projects; in addition, analyses are carried out with SDRs of 10% and 12%.

To estimate the salvage value, the concept of average economic life was applied, which corresponds to the average value of the works as a function of the useful life and weighted cost of the elements of the infrastructure evaluated. Thus, the calculated residual value of the works corresponds to 39% and 60% for flexible and rigid pavement, respectively.

### 3.3.3. Benefits and Economic Indicators

For each alternative, profitability indicators were obtained relative to Net Present Value (NPV), Internal Rate of Return (IRR), Benefit/Cost ratio (B/C), NPV/Investment ratio (NPV/I), the latter being selected for the comparative analyses.

In this research indirect benefits are not considered, since the analyses strictly adhere to the HDM-4 economic model, which quantifies economic benefits based on the *Travel Cost Method* (TCM), widely applied in the area of social feasibility of road projects. Other approaches may include additional benefits, although there is not necessarily a monetary transaction, there is a gain associated with the sense of well-being and health resulting from bicycling that is related to the enjoyment of the activity. According to Wang *et al.* (2004), the overall benefit increases as the environment and conditions for cyclists improve, increasing the frequency of use and the spectrum of associated benefits.

## 4. RESULTS

### 4.1 Modeling Scenario I - Normative Context

Table 5 presents a quantitative analysis of the variation of profitable alternatives as a function of traffic growth rates and the project's social discount rate (SDR), showing that both rates impact the results, but the SDR incidence is higher.

The table above shows the number of profitable alternatives and their respective percentage in relation to the 168 possible alternatives for each traffic category. Naturally, traffic represents the most determinant variable in terms of profitability, a fact that is corroborated by the wide differences obtained among the six demand categories herein analyzed. When traffic does not grow over time, with an initial demand of 500 bicycles/day, the number of profitable alternatives is only 44% of the total analyzed. It is important to note that most of the unfeasible alternatives correspond to the minimum operating speed (15 km/h).

With normal traffic of 750 bicycles per day, there is still an important level of risk, and it is evident that with more challenging SDR and TGR, alternatives are profitable in a proportion

lower than 61% of the total. For demands equal to or greater than 1,000 bicycles per day, economic profitability is a predominant condition, and under the most favorable rates, socio-economic feasibility is achieved in 100% of the possible alternatives.

**Table 6** – Number and % of profitable alternatives

Bikes/day	SDR 8,5%			SDR 10%			SDR 12%		
	Traffic Growth Rate (TGR)								
	0	3%	6%	0	3%	6%	0	3%	6%
	74	102	129	62	87	115	44	66	89
NMT 500	44%	61%	77%	37%	52%	68%	26%	39%	53%
	131	146	159	119	138	152	103	125	142
NMT 750	78%	87%	95%	71%	82%	90%	61%	74%	85%
	152	164	168	149	157	166	137	148	159
NMT 1,000	90%	98%	100%	89%	93%	99%	82%	88%	95%
	167	168	168	159	167	168	152	162	168
NMT 1,250	99%	100%	100%	95%	99%	100%	90%	96%	100%
	168	168	168	167	168	168	162	168	168
NMT 1,500	100%	100%	100%	99%	100%	100%	96%	100%	100%
	168	168	168	168	168	168	168	168	168
NMT 2,000	100%	100%	100%	100%	100%	100%	100%	100%	100%

Regarding the most incident variables and their combinations, it was evident that there are borderline situations in which one of the variables evaluated is a determining factor for the feasibility of an alternative. For example, the feasibility of alternatives with normal traffic of 500 bicycles/day is subject to investments ranging from R\$ 400,000 to R\$ 700,000 per kilometer, always when the operating speed exceeds the value of 20km/h, in other words, it is essential that the project represents a minimum gain of 10km/hour for the user. This situation is maintained even considering the generated traffic in the first years of the project.

Alternatives with higher traffic gradually and favorably increase the results of the economic indicators, but important risks remain for alternatives with normal traffic of 750 bicycles/day, whose viability is tied to investments less than or equal to R\$ 900,000 per kilometer. In addition, the operating speed should be higher than 20 km/h to guarantee positive results. However, high percentages of generated traffic (50%, 100% and 150%) economically compensate for the disadvantages of an operating speed of 15 km/hour, and projects with low to medium investments (R\$ 400,000 - R\$ 900,000 per kilometer) are profitable under these conditions. However, just the maximum initial demand considered (2,000 bicycles per day) reaches full efficiency in terms of profitability.

#### 4.2 Scenario II Modeling - Regional Analysis

Considering the range of investments addressed in this study, the maximum investment allowed for each project alternative is presented in terms of regional per capita income, and the analysis is carried out with the volume of normal and generated traffic in the first two years of operation for the three situations of traffic growth and a SDR of 8.5%. The viability of projects with restricted speed gains are dependent on demand and, relevantly, the economic conditions of the bicycles users as shown in chromatic Figure 5.

According to Figure 5 (a), with an average operating speed of 8 km/h and no growth in demand, bikeway projects are not feasible in most of the city of São Paulo when traffic levels range between 550 and 750 bicycles/day. Only in the Extended Center, whose population was

characterized with an average per capita income of 10.10 R\$/hour, the projects admit investments above 600,000 R\$/km for the minimum demand studied (550 bicycles/day) and projects quickly become feasible for demands above 1,000 bicycles/day with the highest value of the investment range analyzed. Naturally, the most critical situation is presented for the region with high IPVS, whose economic benefits are insufficient to make viable projects even with a volume of 2,000 bicycles/day.

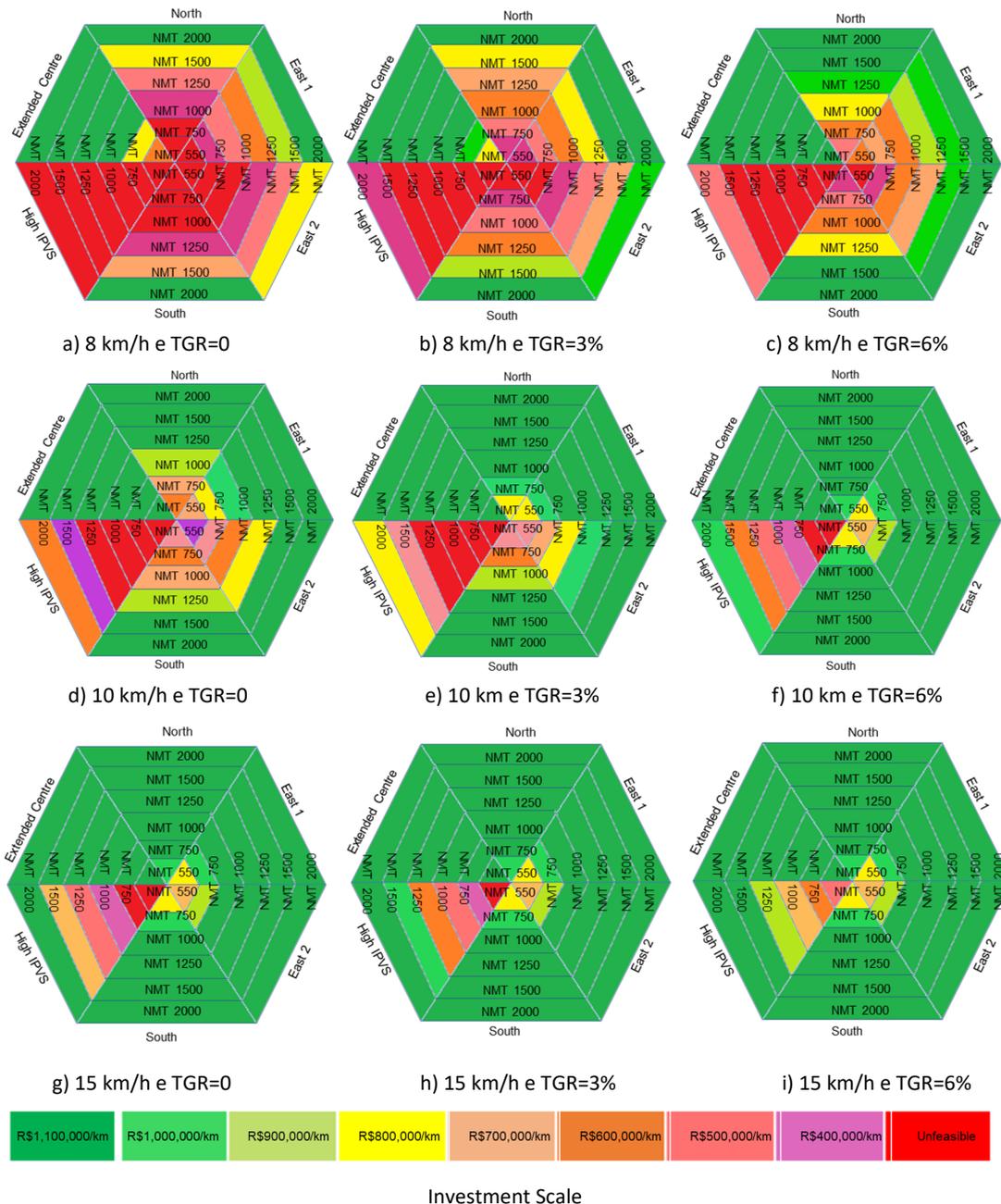


Figure 5. Investment in function of Traffic by each Speed

According to Figure 5 (b) and (c), the economic scenarios with growth rates of 3% and 6% per year, derive more favorable situations for the viability of the projects. In this case, the region with the lowest per capita income reaches social profitability only when demand exceeds 2,000 bicycles/day.

With respect to the operating speed of 10 km/h, the most critical situation is preserved by the region whose users have high IPVS. The admissible investment corresponds to R\$ 600,000/km when the highest demand is projected with a static behavior in the analysis period (Figure 5 (d)).

However, the high non-motorized traffic (2,000 bicycles/day), in the most optimistic condition (annual growth rate of 6%), makes projects with investments equivalent to R\$ 1,000,000/km feasible. In the North, South, East 1, East 2 regions, traffic exceeding 750 bicycles/day admits the maximum investment established in this analysis (Figure 5 (f)). In the Extended Center region, the best profitability conditions are maintained without any risk for any level of investment.

When the operating speed is significantly increased to 15 km/h and a gain of up to 10 km/h is achieved, the user reduces travel time in such proportions that the profitability of the projects is not strictly associated with cycling demand, except in the high IPVS region that represents the greatest risks for cycling projects from the perspective of user direct benefits.

According to Figures 5 (g), (h), and (i), only the traffic of 550 bicycles/day represents budget restrictions for the North, South, East1 and East 2 regions, but it is a range of vast investments that allow the implementation of infrastructure appropriate to the current standards.

Other variables were sensitized to determine the risks of the projects, such as the value of the new vehicle. According to the results, this variable is not very representative for projects developed with users whose profile fits good socioeconomic conditions; however, in projects with the lowest income per capita (High IPVS), even a variable with little incident in the model can imply favorable or unfavorable results, given that these are projects in constant financial risk that become sensitive to slight variations.

Thus, the variation of the unit price of the vehicle (new bicycle) was performed, with decreases of 25% (R\$ 594) and 50% (R\$ 396) in relation to the value adopted in the total analyses, which corresponds to R\$ 792. The sensitivity analyses were performed for non-motorized traffic of 500, 750 and 1000 bicycles/day. The other conditions of the analysis were maintained.

The results showed that this variable has little bearing on the feasibility of projects located in regions with high IPVS and low traffic (500 bicycles/day). However, with traffic higher than 750 bicycles/day and halving the cost of a new vehicle, there are important and positive variations that suggest the need for a proper user profile characterization for specific bicycle projects, especially when bikeways allow a minimum operating speed of 15 km/h and have a high potential to increase user demand.

## 5. CONCLUSIONS

Overall, the non-motorized traffic model of the HDM-4 software proved to be practical and effective in determining the feasibility of bicycle infrastructure projects, quantifying travel time, user costs and benefits as a function of the exogenous and endogenous projects variables. Through the socioeconomic indicators obtained, it is proven that the direct economic benefits of bicycle tracks users can generate feasible projects when the demand is compatible with the investment and the desired speed of operation.

Operating speed is the heart of the Non-motorized traffic model of HDM-4 software, since saving users' travel time becomes a decisive factor for project viability, and its impact is greater

than the incidence of variations in traffic demand or investment in the works. This is demonstrated by analyzing the different travel times and costs through the comparison of different per capita income levels, the results of which show the budgetary constraints when some project variable results in some risk to the project.

Regarding the profitability and benefits of project alternatives, the following results and considerations stand out below:

- The best results, in terms of profitability, correspond to traffic above 1,000 bicycles/day. From this category of traffic on, situations that do not suggest high risks in terms of investment recovery are predominant. In any case, it should be mentioned that only the demand equivalent to 2,000 bicycles/day guaranteed absolute economic efficiency in all the scenarios evaluated.
- As for the low traffic (500 - 750 bicycles/day), the results raise a reflection on the operating conditions that justify the construction of bike lanes in places with low demand whose implementation work corresponds to high investments. Even with high percentages of traffic generated in the first years of implementation, the investments are in a risky situation whose return depends on very good operating conditions and challenging traffic growth.
- Such assessment alludes to some realities presented in this document about the average volume of bicycles that circulate on bicycle paths in São Paulo. It is pertinent to mention that according to available CET records, 50% of bicycle paths have a traffic lower than 1,000 bicycles/day and some elements have such low traffic that currently they do not suggest very optimistic situations about demand behavior.
- The importance of the correct definition of the social discount rate is emphasized, since its variation generate the profitability or rejection of a prominent number of project alternatives. In this sense, it is convenient that the public or private agency evaluates planning policies and financing conditions of bicycle paths projects.

Finally, it should be noted that since this is an analysis at the network level, the modeling results should be interpreted in a referential way, and not as an absolute technical-economic behavior, since the results of specific projects will always depend on the pavement typology, the network and regional characteristics, the user profile and the objectives of the particular project or network. In addition, the socioeconomic analysis must constitute a phase of planning, being preceded, necessarily, by interdisciplinary technical studies as any road project.

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