Estimating freight demand for North-South Railway: a Brazilian case study

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ABSTRACT. The main goal of this paper was to propose a model to estimate the freight demand for Brazil's North-South Railway. The evaluation of the amount of cargo that could be attracted by the railway was done through the use of a linear optimization network flow model. In 2005, the results showed a total of 1.0 million tons of inter-regional soybean flows that have potential to be moved through this rail line between Estreito (MA) and São Luís (MA). This model is practical tool for evaluating the potential flows through a transportation infrastructure and for identifying the origins and routes related to these flows. The present research also offers valuable inputs for transportation strategic planning.

INTRODUCTION

The Brazilian transportation system did not follow economic growth of the last decade. As a result of insufficient government investment the Brazilian transportation infrastructure has became outdated, reaching a critical situation, labeled by specialists as the logistic "blackout".

Due to the large extension of Brazil territory, the major participation of the road mode in freight transportation is one of the factors which contribute to the inefficiency of the transportation sector in the country. According to Barat (1978), this scenario has its origins in the 30's, when the transportation policies focuses exclusively on the develepoment of road transportation. Since then, the resources available for the investment in transportation have been allocated mainly to the construction and maintenance of roads. This fact has caused an unbalance in the national transportation modal share. On one side there is a preponderance of the road and on the other side there is a small participation of barge and rail freight transportation.

Recently, new trends in the Brazilian cargo transportation sector have concurred to changes in this critical scenario. The cargo flow through railways has shown relatively high increasing rates over the last years, mainly between 2002 and 2006. Garrido (2006) shows that

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investments made by the railway concessionaires have led to a revival of the rail transport in Brazil and to its higher contribution to the national cargo transportation.

Regarding the railway system, which had not experienced any improvements in ages, two old projects that was stopped due to the vacuum of investments had their works started. In 2006 the first steps for the construction of the Trans-Northeastern Railway were taken and also the works on the North-South Railway were restarted.

The North-South Railway operation, maintenance and improvements are under the responsibility of Vale do Rio Doce Company, which won this concession on October 3rd 2007. This railroad when ready will connect the cities of Senador Canedo (GO) to Belém (PA). It has access to Itaqui port (MA) through the Carajás Railroad. Nowadays, the stretch of this railroad between Estreito (MA) and Açailândia (MA) is already in operation (see Figure 1), the stretch between Estreito (MA) and Araguaína (TO) is already finished but not in operation and the next extension of the railroad to Palmas (TO) is scheduled to be ready in 2008.

Although railroads play an important role in regional economic development, the building of a railroad consumes high levels of investments. In the case of the North-South Railroad, according to Valec (2006), the costs for concluding the entire project reach a total of US$ 1,4 billions. If a region does not present a favorable scenario for cargo transportation through the railroad, the project will not be sustainable in the long term. A railroad shows very high fixed costs and, therefore, requires huge volumes of cargo to generate sufficient income to ensure its economic viability.

In this context, studies of demand for rail transport present themselves as primordial tools to examine the economic viability of a railroad project and also for the strategic planning of its infrastructure.

Objectives

Considering the important support that a study of freight demand can offer to a transportation system strategic planning, this paper aimed to present a linear programming model that can be used to evaluate the captive potential cargo by a new transportation infra-structure in its area of influence, in order to generate a basis for its strategic planning.

A linear optimization model, referred to in the literature as the *Multicommodity Minimum Cost Flow Problem*, is being proposed as a tool to evaluate the freight demand for North-South Railroad. As soybean is the main cargo produced in the area of influence of this railway, the proposed model was applied to evaluate the total cargo of soybeans that has potential to be moved through this new transportation way.

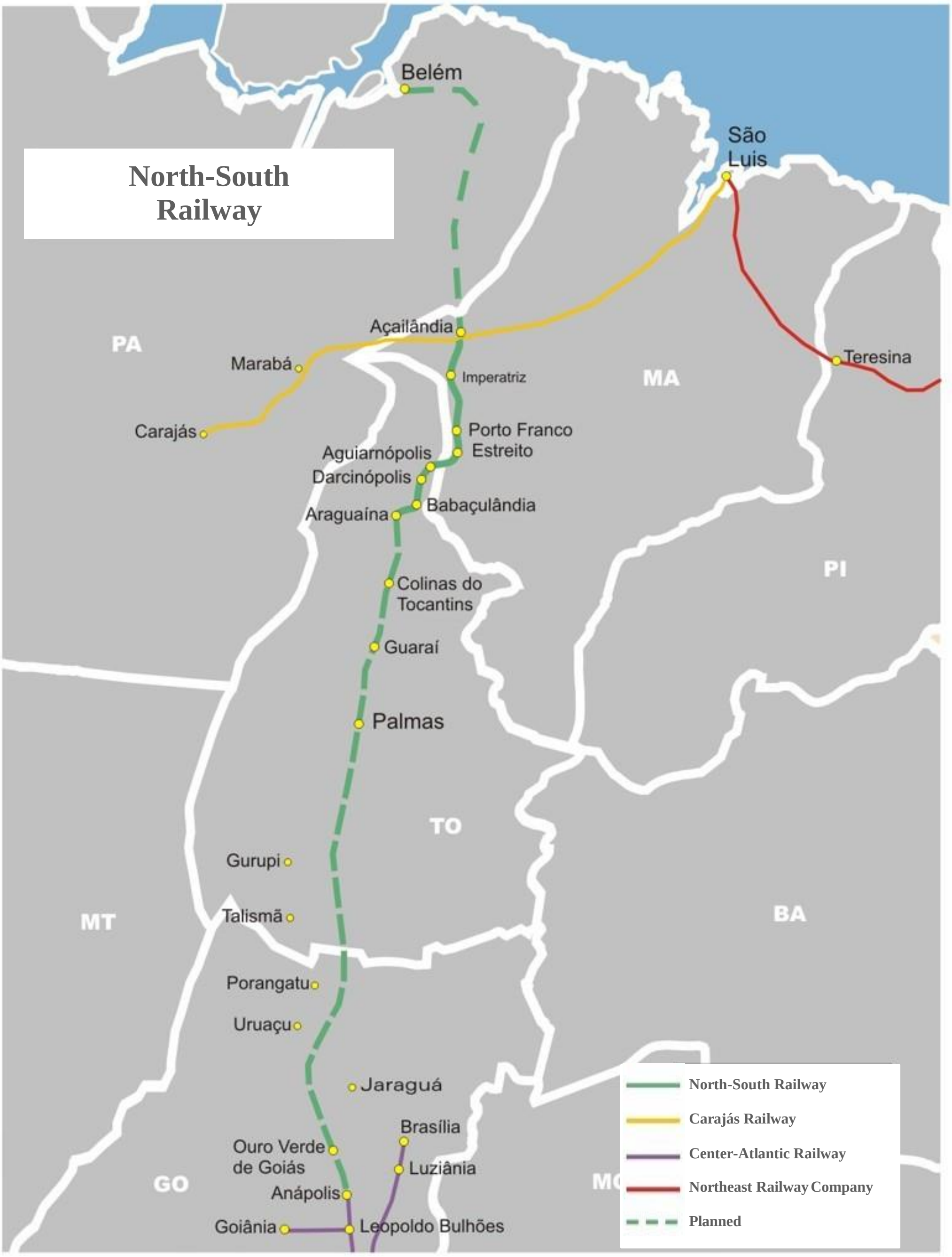

Figure 1. North-South Railroad
Source: National Agency for Land Transportation - ANTT (2006), modified by the author

Models utilized for estimating cargo demand

Until the mid 70's it was notable the lack of models for estimating the flow of cargos inter-regions. Until then, the models focused on the techniques of simulation and estimates of demand for passenger transportation. The first model of flow estimates inter-regions focused on cargo transportation is referred to in the literature as the *Harvard Model*. Due to the importance of the analysis and flow estimates between locations for the strategic planning of the transport system, new studies provided support to the development of models to meet such need. A series of models of multimodal and multi-product transport was presented in the 80's and 90's showing more elaborated representations of the transport system. Some of them allowed the use of functions of non-linear transportation costs and were sensitive to

economies of scale. They took into consideration the effects of traffic jams found in railroad stretches of the multimodal network, they simulated delays caused by operations in railroad facilities and stations or even considered the movements of empty wagons and specific wagons for each type of product in the railroad system.
The most used models for simulating and estimating cargo demand can be divided into three major classes: Spatial Price Equilibrium Models, Discrete Choice Models, and Network Equilibrium Models.

According to Friezs and Harkers (1983), the concepts involved in the Spatial Price Equilibrium Models were originally developed by Samuelson (1952) and later expanded by Takayama and Judge (1964). The authors report that in the most cases these models involve the interaction among producers, consumers and shippers. The transportation costs are established exogenously instead of being determined through the carrier's decision simulating. The behaviors of consumers and producers are incorporated into these models making use of the demand and supply functions.

Regarding the Discrete Choice Models, Monteiro et al. (2001) highlight that this modeling technique is based on the fundaments of the consumer economic theory and on "behavioral" models. According to the authors, the Discrete Choice Models consider that the shipper aims to maximize their utility function, which depends of the characteristics inherent of each transportation alternative. The set of attributes of each alternative of transportation characterizes the level of satisfaction of the shipper and the utility function is determined based on Discrete Choice Models just as Logit and Probit.

Friezs and Harkers (1983) approach the theoretical concepts that constitute the models of Network Equilibrium Models. According to them, the focus of this class of models is on the interactions between shippers and carriers. Contrary to Spatial Price Equilibrium Models, which consider the supply and demand functions determining the amounts of cargo produced and demanded in a given zone, the Network Equilibrium Models establish the amounts of supply and demand as exogenous variables.

Ahuja et al. (1993) suggest a linear model of network flows optimization, which can also be applied for predicting demand for freight transportation. The problem, denominated Multicommodity Flow Problem, considers the minimization of the total transport costs of network flows, whose arcs are shared for more than one product. This model is very practical because does not require the calibration of supply and demand functions or other parameters needed on the formulation of more complex models, once they are already treated as exogenous variables. The linear formulation of the model ensures a global optimum solution.

Besides, the data of supply and demand on each nodes and the impedance associated to the arcs are the only requisites for the application of the model to simulate network flows.
The model proposed for this study was developed based on the concept of *Multicommodity Flow Problem,* being applied in a multimodal transportation network.

MATERIAL AND METHODS

Spatial division in zones and choice of centroids

The spatial division adopted to meet the scope of this study was based on a sub-division of Brazilian states in areas with economic and social similarities, proposed by the Brazilian Institute of Geography and Statistics – IBGE, denominated Meso-regions and Micro-regions. In the case of states located into the North-South Railway area of influence – defined in this study as the area delimited by the states crossed by the North-South Railroad and the neighboring states, involving Goiás (GO), Tocantins (TO), Bahia (BA), Maranhão (MA), Piauí (PI), Pará (PA) and Mato Grosso – the corresponding Micro-regions were adopted as the spatial division framework; for the other Brazilian states, they were divided into Meso-regions.

The centroids choice for the territorial zones was done considering the most populous cities of each Micro-regions or Meso-regions. The demographic data was obtained from the Demographic Census of IBGE.

Proposed mathematical model

The flow assignment between the Origin-Destination (O-D) pairs was done making use of a linear optimization model, which has as objective to minimize the total cost of freight transportation.

As for the choice of possible routes and transportation modals between the centroids which result in the lower global transportation cost, it was developed a model based on the *Multicommodity Minimum Cost Flow Problem* (see Figure 2), presented by Ahuja (1993). It is important to point out that the proposed model does not take into account a multicommodity approach, being the results processed and analyzed individually for each product.

In order to attend the context of this study, a few adjustments were made on the *Multicommodity Minimum Cost Flow Problem*, being proposed the mathematical structure presented as follows:

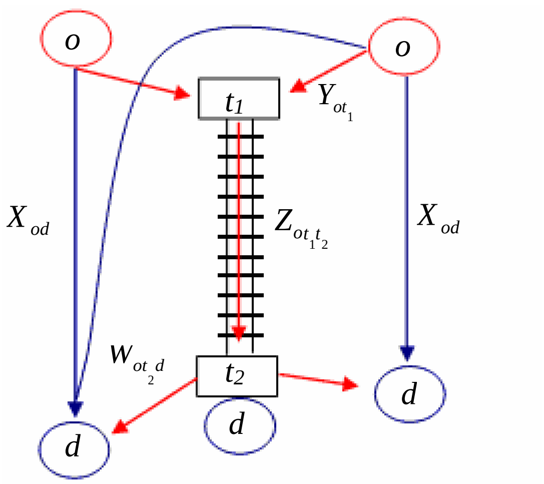

Figure 2. Representative graph of Multicommodity Minimum Cost Flow Problem
Source: adaptated from Ahuja (1993)

Minimize the total logistic cost expressed by:

$$\sum_{o=1}^{n}\sum_{d=1}^{m} X_{od} \times FX_{od} + \sum_{o=1}^{n}\sum_{t_1=1}^{r} Y_{ot_1} \times FY_{ot_1} + \sum_{o=1}^{n}\sum_{t_1=1}^{r}\sum_{t_2=1}^{q} Z_{ot_1t_2} \times FZ_{ot_1t_2} + \sum_{o=1}^{n}\sum_{t_2=1}^{q}\sum_{d=1}^{m} W_{ot_2d} \times FW_{ot_2d} \quad (1)$$

subject to the following constraints:

$$\sum_{d=1}^{m} X_{od} + \sum_{t_1=1}^{r} Y_{ot_1} = SUPPLY_o, \quad \forall \quad o \quad (2)$$

that is, the sum of the product flows p moved from the origin centroid o through the road route to any destination centroid plus the sum of product flows p moved from the origin centroid o to any initial transfer node (t_1) , must be equal to the level of product p supplied by the origin centroid o. This restriction ensures that all supply of a centroid be shipped.

$$\sum_{o=1}^{n} X_{od} + \sum_{o=1}^{n}\sum_{t_2=1}^{q} W_{ot_2d} = DEMAND_d, \quad \forall \quad d \quad (3)$$

that is, the sum of the product flows p moved from any origin centroid through the road route to the destination centroid d plus the sum of product flows p moved from any final transfer node (t_2) to the destination centroid d, must be equal to the level of product p demanded by the destination centroid d. This restriction ensures the supply of the demand of each destination centroid d.

$$Y_{ot_1} = \sum_{t_2=1}^{q} Z_{ot_1t_2}, \quad \forall \ o \quad and \quad t_1 \quad (4)$$

that is, the product flows p moved from the origin centroid o to the initial transfer node t_1 must be equal to the sum of flows originated in o between the point of the initial transfer node t_1 to any final transfer node (t_2). This restriction ensures the continuity and the balance of product flows p originated in o which passes by the initial transfer node t_1.

$$\sum_{t_1=1}^{r} Z_{ot_1t_2} = \sum_{d=1}^{m} W_{ot_2d}, \quad \forall \quad o \quad and \quad t_2 \quad (5)$$

that is, the sum of the product flows p moved from the origin centroid o which pass by any initial transfer node (t_1) and that are going to a certain final transfer node t_2 must be equal to the sum of the product flows p moved from the final transfer node t_2 to any destination centroid. This restriction aims to ensure the continuity of the product flows p originated in o which passes by the transport point t_2.

$$\sum_{d=port\ 1}^{port\ s} X_{od} + \sum_{t_2=1}^{q} \sum_{d=port\ 1}^{port\ s} W_{ot_2d} \geq EXPORTS_o, \quad \forall \quad o \tag{6}$$

that is, the sum of the product flows *p* moved from the origin centroid *o* through the road route to any destination centroid - considering only the ports - plus the sum of product flows *p* moved from the origin centroid *o* passing by finals transfer nodes and going to any destination centroid - also considering only the ports, must be higher than or equal to the exports level of the product *p* offer at the origin centroid *o*. This restriction ensures that the fraction of the supply of the product *p* equivalent to exports level at each origin be allocated to destination centroids which are ports.

$$\sum_{o=port\ 1}^{port\ s} X_{od} + \sum_{o=port}^{port\ s} \sum_{t_2=1}^{q} W_{ot_2d} \geq IMPORTS_d, \quad \forall \quad d \tag{7}$$

that is, the sum of the product flows *p* moved from any origin centroid - considering only the ports - through the road route to a destination centroid *d* plus the sum of product flows *p* moved from any origin centroid – also considering only the ports - passing by final transfers nodes and going to the destination centroid *d*, must be higher than or equal to the imports level of the product *p* demanded at the destination centroid *d*. This restriction ensures that the fraction of the demand of the product *p* equivalent to imports level at each destination be allocated from origin centroids which are ports.

More specific meanings of the parameters and variables considered in this mathematical model are presented as follows:

X_{od} : quantity (tons) of product *p* moved from the origin centroid *o* to the destination centroid *d*;

FX_{od} : freight value (R$/ton) for the transport of product *p* from origin centroid *o* to the destination centroid *d*;

Y_{ot_1} : quantity (tons) of product *p* moved from the origin centroid *o* to the transfer node t_1;

FY_{ot_1} : freight value (R$/ton) for the transport of product *p* from the origin centroid *o* to the transfer node t_1;

$Z_{ot_1t_2}$: quantity (tons) of product *p* moved from the origin centroid *o* which pass between the initial transfer node t_1 and the final transfer node t_2;

$FZ_{t_1t_2}$: freight value (R$/ton) for the transport of product *p* between the initial transfer node t_1 and the final transfer node t_2;

W_{ot_2d} : quantity (tons) of product *p* moved from the origin centroid *o* wich pass by the final transfer node t_2 going to destination centroid *d*;

FW_{t_2d}: freight value (R$/ton) for the transport of product *p* between the final transfer node t_2 and the destination centroid *d*;

$SUPPLY_o$: level of supply (tons) of product *p* at the origin centroid *o*;

$DEMAND_d$: level of demand (tons) of product *p* at the destination centroid *d*;

$EXPORTS_o$: level of exportation (tons) of product *p* at the origin centroid *o*;

$IMPORTS_d$: level of importation (tons) of product *p* at the destination centroid *d*.

n: index referent to the total number of origin centroids;

m: index referent to the total number of destination centroids;

r: index referent to the total number of initial transfer nodes for alternative modals to the road transport (railway and/or river transport);

q: index referent to the total number of final transfer nodes for alternative modals to the road transport (railway and/or river transport).

Therefore, in order to identify flows through the railway – the main subject of this study – the analysis of the model results focused on values assumed by the variable $Z_{ot_1t_2}$ (quantity of product *p* moved from the origin centroid *o* which passes between the initial transfer node t_1 and the final transfer node t_2), correspondent to the North-South Railroad. This variable also represents the flow through other transport ways competitors to this railroad, when the transfer nodes t_1 and t_2 belong to others modes of transport.

The mathematical model was solved through the use of the Cplex solver, with the use of the software General Algebraic Modeling System – GAMS.

Supply and demand data

Production: it was used the data of municipal soybean production reported by the study on agricultural harvests carried out by IBGE, named Municipal Agricultural Production 2005.

Consumption: from the amount of soybean processed in Brazil in 2005, informed by the Brazilian Association of Vegetal Oil Industry (ABIOVE, 2007), the soybean consumption was estimated through the fractioning of the national soybean consumption into municipal consumption, proportionally to the crush capacity of soybean crushers unit, reported on the study of Safras & Mercados (2003)[3].

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[3] Safras & Mercados. **Capacidades.xls**. São Paulo, 2003 (private communication).

Exportation and importation data

The estimation of the quantity of cargo that was exported or imported by each zone was based on the information for 2005 regarding the exports and imports reported by the Brazilian international trade secretary – SECEX.

Representation of the road transportation system

The road distances were obtained through a database on road distances supplied by LOGIT (2006)[4].

The representation of the Brazilian railway network was done through selecting municipalities nearby the Brazilian railway system, corresponding to the real transfer nodes, and through determining the railway distances between these locations. The transfer nodes were selected from choosing the main locations which have access to the Brazilian railway system. The distances between the transfer nodes were supplied by LOGIT (2006) and correspond to the real physical distances of the railway system.

Estimates for transportation costs

In order to estimate road freight values, it was used real soybean freight values negotiated in the North-South Railway area of influence, referring to the year 2005, supplied by SIFRECA (2007)[5]. Due to the fact that there is not freight information to all possible combinations of routes considered by the model, the value of the road transport was estimated with the use of a model of linear regression between freight values and distances, using the Method of Minimal Squares Roots.

The railway transportation costs were estimated from the costs of road transport between initial transfer nodes and final transfer nodes, obtained by applying a discount of 30% under the road freight estimated value on each network arc.

More detailed information of estimating freight values adopted method is available at Branco (2007).

RESULTS AND DISCUSSIONS

The prediction of the potential amount of soybean to be moved through the North-South Railway fixed the 2005 year as a basis. The results were obtained considering two scenarios involving distinct configurations of the railway infra-structure: the currently configuration of the North-South Railway and the one that includes the expansion of the rail branch-lines planned by the Brazilian Government.

The first scenario - denominated "Current Scenario"- contemplates only the railroad line currently in operation that connects Estreito (MA) to Itaqui Port, located in São Luís (MA), through the Carajás Railroad. The second scenario, denominated "Planned Branch-lines Scenario", also includes the Northern branch-line, connecting Lucas do Rio Verde (MT) to Miracema do Tocantins (TO), and the Mid-North branch-line, connecting Balsas (MA) to Açailândia (MA). Figure 3 provides a better visualization of the proposed scenarios.

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[4] LOGIT Consulting Engineering Ltda. **Distâncias.xls**. São Paulo, 2006 (private communication).
[5] SIFRECA Freight Information System. **Fretes.xls**. Piracicaba, 2006 (private communication).

Figure 3. North-South Railway with the Northern and Mid-North branch-lines

"Current Scenario"

The total soybean loads suggested by the model with potential to be moved through the North-South Railway (NSR) amounted roughly 1.0 million tons. Analyzing all soybean flows originated in the NSR area of influence, it was verified an important participation of the Ferro-Norte Railway as an alternative for transporting the soybean harvested from Mato Grosso state, being observed results that indicate a total movement of 3.7 million tons through this railway. Another important transportation route in the same area of influence is the barge transportation through the Madeira River, having the results shown flows that amount up to 1.4 million tons with potential to be transported through this alternative of transport. In the case of the centroids located in the Central, Southern and Southeastern of Goiás state, the model indicated important soybean flows originated in these regions for movement through the Center-Atlantic Railway, mainly in the rail lines between Goiânia (GO) and Santos (SP) and, also, in the rail lines that connect Uberlândia (MG) to Vitória (ES).

From a more detailed analysis of the soybean flows with potential to be moved through NSR, it was observed that its major part has been originated in the Micro-region *Gerais de Balsas* (MA), which accounted for almost 59% of all soybean loads allocated to the NSR. Also, the Micro-regions of Porto Nacional (TO) and Miracema do Tocantins (TO) were important zones of cargo supply to the NSR, whose results show participations of, respectively, 15% and 7% of the total soybean flows with potential to be transported through this railroad, according to what can be observed in the results presented in Table 1.

Table 1. Railway soybean flows indicated by the model for movement through the NSR and participation of each flow in relation to the total transported through the railroad ("Current Scenario")

Zone Centroid	Transfer node t_1	Transfer node t_2	Potential loads (10^3 tons)	Share (%)
Balsas_MA	Estreito_MA	São Luís_MA	577.65	58.50%
Palmas_TO	Estreito_MA	São Luís_MA	151.23	15.32%
Miracema do Tocantins_TO	Estreito_MA	São Luís_MA	75.65	7.66%
Gurupi_TO	Estreito_MA	São Luís_MA	57.15	5.79%
Paraíso do Tocantins_TO	Estreito_MA	São Luís_MA	56.03	5.67%
Araguaína_TO	Estreito_MA	São Luís_MA	27.14	2.75%
Estreito_MA	Estreito_MA	São Luís_MA	26.94	2.73%
Conceição do Araguaia_PA	Estreito_MA	São Luís_MA	14.87	1.51%
Redenção_PA	Estreito_MA	São Luís_MA	0.77	0.08%
Total			987.43	100%

It is important to point out that this railway transported exclusively soybean in 2005, totaling 1.2 million tons, according to data from The National Agency for Road Transportation. When compared to the soybean flows indicated by the model ("Current Scenario"), which amounted roughly 1.0 million tons, it can be observed that such amount of estimated potential cargo to be transported through the NSR was very close to the actual amount transported through the railway.

"Planned Branch-lines Scenario"

The results related to this scenario show new important flows of soybean originated in the Mato Grosso state, mainly in the Micro-region of Sorriso (MT), which pass by the transfer node of Lucas do Rio Verde (MT) going to Itaqui Port, in São Luís (MA). Also, it was observed an important movement of soybean originated in the Micro -region of Confresa (MT) destined to Itaqui Port. The results revealed that the Mid-North branch-line did not stimulate an increase in the soybean cargo by the NSR in relation to the "Current Scenario". However, the total amount of potential soybean loads to be transported through the NSR amounted up to 1.7 million tons, therefore higher than the movement of this product observed in the first scenario. The results point out as the main zones that showed potential cargo the Micro-regions of Alto Teles (MT), Balsas (MA) and Norte Araguaia (MT).

Table 2. Railway soybean flows indicated by the model for movement through the NSR and participation of each flow in relation to the total transported through the railroad ("Planned Branch-lines Scenario")

Zone Centroid	Transfer node t_1	Transfer node t_2	Potential cargo (10^3 tons)	Share (%)
Sorriso_MT	Lucas do Rio Verde_MT	São Luís_MA	645.42	38%
Balsas_MA	Balsas_MA	São Luís_MA	577.65	34%
Confresa_MT	Confresa_MT	São Luís_MA	154.27	9%
Palmas_TO	Palmas_TO	São Luís_MA	151.23	9%
Paraíso do Tocantins_TO	Palmas_TO	São Luís_MA	56.03	3%
Paragominas_PA	Açailândia_MA	São Luís_MA	50.95	3%
Gurupi_TO	Gurupi_TO	Palmas_TO	30.55	2%
Estreito_MA	Estreito_MA	São Luís_MA	24.24	1%
Araguatins_TO	Imperatriz_MA	São Luís_MA	8.34	0%
Miracema do Tocantins_TO	Palmas_TO	São Luís_MA	6.60	0%
Estreito_MA	Estreito_MA	Palmas_TO	2.70	0%
Total			1708.00	100%

Analysis of results

It is important to underscore that there are several factors interfering in the decision of shippers concerning the destination of their production transportation and related to the choice of the best alternative of transport. For example, the shippers involved in a transportation system can make the decision to move their production to a specific destination taking into account the prices offered in each market and not only based on transportation costs. The choice of a transportation mode is also a complex process and can be influenced by a series of transportation attributes, such as: flexibility, transit time, frequency, reliability, costs, level of traffic, among others. As it was presented before, the literature offers a series of models for predicting intercity flows and freight transportation demand which try to describe in more details the operational aspects of a railway and the behavior or decision of the agents involved in a transportation system (shippers and carriers). Overall, these models objective to represent and simulate as real as possible the processes involved in the decision-making process of shippers and carriers; nevertheless, as more complex models are developed, new type of parameters are required, whose calibration and adjustments involve hard field work. Besides, many of these models comprehend non-linear equations, which can be harder to be solved and, in many cases, unable to indicate a global optimal solution.

In other way, due to fact that the soybean is considered a commodity with relative low added value and also observing an important weight of the transportation costs on its final price, it is reasonable consider the transportation costs as the main attribute which interferes in the decision-making of shippers for the movement of this type of cargo.

CONCLUSIONS

The application of the proposed model can generate important information inputs for studies of new transportation infra-structure economic viability, for the decision of rail lines lay-out, for the analysis of competition between different transportation modes and the assessment of other questions which give support to the planning and regulating activities regarding the freight transportation systems.

About the results of this study, they allowed the identification of the main zones that offer potential cargo to be moved through the North-South Railway. This type of information is rather relevant once it indicates the zones that present freight flows to be captured by this railway, that is, which allows the identification of regions that may become a client of such transportation infra-structure.

Another type of useful information obtained through the proposed model is the indication of the amount of cargo which passes by each transfer node. The analysis of these results generates important support for the choice of places with potential to become transshipment points.

The evaluation of impacts derived from expansion of the railway lines on the freight demand is also an important output to support the decision of agents involved in the strategic planning of a railway. This type of analysis is essential when one measures the benefits or incomes which would be derived from such a project.

The estimation of the demand for potential cargo offers support for dimensioning the road infra-structure, the fleet of vehicles and other equipment needed for moving the flows of products and, also, for estimating the income that would be generated from transporting them through that railroad. This is vital information for the analysis of the economic feasibility of the railway.

Due to the fact that the results correspond only for the year-basis 2005, it is suggested that the proposed model be applied considering projections for future level of supply and demand loads at each zone. It is known that railway projects involve long periods for the amortization of the initial capital being, therefore, of fundamental importance the estimation of cargo flows through the railway for longer periods of time.

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