SYSTEM DYNAMICS
Long term forecasting of road traffic volumes

J. Manuel Viegas, CESUR – Instituto Superior Técnico; and
TIS – Transportes Inovação e Serviços (viegas@tis.pt)
N. Miguel Martins, TIS – Transportes Inovação e Serviços (nuno.martins@tis.pt)

Abstract

Traditional traffic volume forecasting models (multivariate linear regression models, calibrated over historical series of traditional variables, such as GDP, car ownership and fuel prices), although generally accepted and suitable for short and medium term projections, are unable to successfully incorporate in their mechanisms and results the direct and indirect interactions (feedback loops) between variables.

It was precisely the major role of these interactions in a long term forecasting model, as well as the recent raising of "new" variables, generated by the current conditions and circumstances over energetic and environmental issues, that led us to develop a new traffic volume forecasting model, based on a system dynamics framework.

Consequently, we designed and calibrated "new" interactions and implications between traditional and new variables, such as emission of green house gases, evolutions of vehicle technology (alternative propulsion vehicles vs. internal combustion engine vehicles), their impact on the vehicle fleets and the introduction of bio-fuels in the market.

This sort of models allows us to comprehend in which ways, in a long term horizon, is it expectable for the road traffic volumes to affect and to be affected by these new variables and how these feedback loops will work together, creating a cross-limitation effect that will drive the model to an internally balanced evolution, made possible by the use of system dynamics.

Introduction

Traditional road traffic forecasting models (multivariate linear regression models, calibrated over historical series of traditional variables, such as GDP, car ownership and fuel prices), although generally accepted and suitable for short and medium term projections, are unable to successfully incorporate in their mechanisms and results the direct and indirect interactions (feedback loops) among some of those variables.

These traditional models, which base their evolution patterns on stable relations between variables, fail when dealing with new paradigms and shifts on mobility standards. This happens as these traditional models are built upon historical relations that, although logical and verified in the past, may not be reasonable and verifiable in the future.

This paper presents the main driving concepts and relations used by the authors in the development of a computer model to estimate long-term traffic growth trends on the Portuguese motorway system, as well as the method adopted for the gradual construction of this model of rather high complexity.

Past vs. Future Evolution

The introduction of a new paradigm, such as electric vehicles [1] or tougher controls on carbon emissions, may create new behavioral models and new interactions between already existing and new emerging variables.

The fuel price analysis, considering the existence of the electric vehicles, has to be made from a different approach, as it is no longer indexed exclusively to petro-fuels (diesel and gasoline), and electricity as vehicle energy vector must be taken into account, with significant price changes introduced with this new approach.

The greenhouse gases (GHG) emitted by these new vehicles will be significantly different from the ones emitted by internal combustion engine (ICE) vehicles, although this will vary depending on how the electricity is generated. This has to be taken into account in a long term projection as limitations on GHG emissions are now globally accepted as mandatory for environmental reasons [2][3][4][5].

The balance between these new elements on fuel price analysis and GHG emissions will determine the evolution of petro-fuels demand and the environmental pressure associated with the degree of non-compliance with emissions targets, with the consequent effects on oil demand/price and on taxation of road transportation for demand management [6].

On a parallel track, the strong progress that has been occurring in multiple dimensions of telecoms, increasingly allowing replacement of some types of mobility by the use of telecommunications, has to be considered. This replacement of mobility is associated with the price, comfort, reliability and sophistication of the telecommunication solutions of the day, but it can be stimulated by other factors, like the spread of contagious diseases (e.g. the SARS case in 2003) and also possibly by the emerging issues referred above, like fuel prices and taxation of car use led by environmental pressure.

Furthermore, replacement of mobility is not only driven by these factors, it is also a driver to them, on a negative feedback loop (stabilizing) model where high mobility prices favor mobility replacement by telecoms, and this reduction of mobility will reduce the pressure on fuel consumption and associated GHG emissions, with consequent reductions on fuel prices and environmental pressure, and with it a stimulus to increasing mobility, until a new point of equilibrium is reached.

In addition, other aspects, disregarded on traditional forecasting, should be taken into account when dealing with long term forecasting: Stronger penetration of bio-fuels [7], vehicle-to-grid (V2G) systems associated with electric cars [8], new business models for fleet renewal including conversion form ICE to electric motor, etc., are examples of such aspects we tried to incorporate in our forecasting model, with all their interdependencies.

System Dynamics

This complex structure of variables and intricate relations and inter-dependencies existing among them led to the conclusion that multivariate-regression traditional models were no longer suitable to meet the challenge. So, we used an approach based on a system dynamics framework, as it is capable of adequately representing the feed-back loops, time delayed relations and variable interactions indispensable in a forecasting model for a 30 year horizon.

System dynamics is a methodology created in the 1950s by Jay Wright Forrester, a professor at the Massachusetts Institute of Technology, as an approach to understanding, describing and forecasting the behavior of complex systems over time.

The central concept to system dynamics is understanding and describing the interactions among the variables in a system. Based on non-linear control theory, system dynamics attempts to mathematically describe the basic structure of a system, and thus forecast the behavior it can produce. System dynamics models are built upon 3 basic concepts:

- Loops – Variable interactions that form feedback loops that affect either positively or negatively the variables present in these loops;
- Stock and Flow – The interactions between variables in system dynamics are usually in the field of differential equations and that results in the existence of 2 main types of variables:
    - Stock Variables – measurable at one specific moment, accumulating or depleting over time;
    - Flow Variables – which depict the instant variation of Stock Variables, and therefore are usually measured per unit of time;
- Equations – mathematical description of variable interactions.

While initially built and used for economic/business purposes only, System Dynamics is now broadly used in such fields as science, socioeconomics, population studies or environment studies [9].

Gradual Implementation (building and calibrating the model)

The implementation and calibration of such a complex model came up as a challenging task, especially considering the amount of variables we decided to take into account, and the “temptation” to promptly introduce them all into the model.

The only way one can build and calibrate a system with such complexity and dimension is to take a top-down approach, i.e., designing the fundamental large scale structure of the system as macro blocks of related variables, understanding and describing the relation between these macro blocks and only then proceed to the next lower level, with the mathematical description of variables and calibration of relations within these blocks.

We took as an opening point to our system a scheme of a traditional regression forecasting model, and starting from there we added up variables and their interactions as we felt the advantage of incorporating them into the model.

The calibration of interactions started mostly on a variable-to-variable basis, meaning that for each pair of interconnected variables we would focus on, describe and calibrate the relation between them, regardless of other interactions between variables outside this pair. These calibrations were based on historical relations, where possible, but for many of the variables related to emerging issues there are no statistical data series to study and extrapolate from, and therefore we had to conduct serious literature search about these issues to understand and be able to assess about what behaviors are expected in the future, rather than extrapolating from what behaviors are known to have happened in the past.

Even though a great quantity of bibliography is available about subjects such as GHG emissions and targets, fiscal stimulus/taxation of car use, vehicle technology, electric vehicles, V2G, bio-fuels, etc., the mathematical definition of each variable and, specifically, its relation with other variables requires in the current state of knowledge some personal intuition and anticipation of what are more or less likely behaviors.

Having to apply this personal intuition over these issues we calibrated our model using what we ended up calling “plausibility and humility”. Plausibility in the sense that in a stable and peaceful society “smooth” evolution curves are expected and it is not reasonable for variables that depict real world human behavior to be subject to steep and abrupt changes, except in situations of deep crisis.

Humility comes into play as we have to assume that our knowledge is limited with respect to the pace of evolution of several of these topics and their interdependencies, which recommends careful and critical analysis of intermediate results and regular use of sensitivity analysis to check the stability of the outputs of the model.

The real Project

Design

In 2008 an international investment fund contacted us in order to produce a study that would produce a forecast for the evolution of road traffic in the Portuguese motorway network over a 30 year horizon. This paper focuses on the work carried out for the development of a global organic growth model, i.e., natural traffic growth for the global Portuguese road network, excluding exogenous factors, such as induced demand by new motorway links, traffic redistribution (competition/ cannibalization), ramp-up and others.

As mentioned above, the starting point towards the implementation of this model was a traditional regression model, to which we added and calibrated in succession new macro-blocks of variables and their relations, so that at anytime we would have a stable and functioning model of growing complexity.

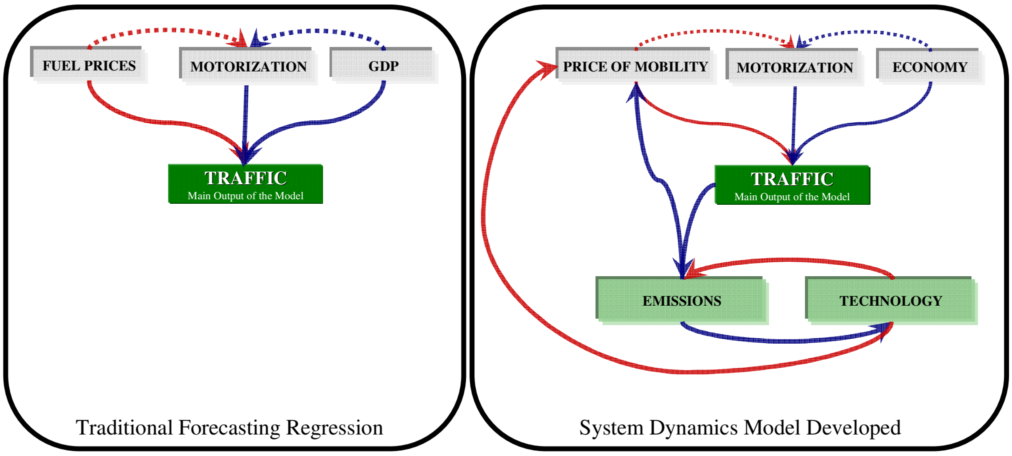

Figure 1 - Schematic representation of the developed model

The basic elements of the starting model are the relations between Traffic and three main explanatory variables: Fuel Prices, Motorization (number of circulating vehicles per 1.000 inhabitants) and GDP (Gross Domestic Product). It must be said that the values for GDP already include the (rather small) variations of population. In this starting model, the variation of traffic is explained only by the variation of these variables, specifically; traffic variation will respond positively to positive deviations of GDP and Motorization and negatively to positive deviations of Fuel Prices.

Additionally, second order interactions between explanatory variables are usually considered, like the positive impact of GDP growth on Motorization or the negative impact of persistent Fuel Price growth on Motorization.

In our new model, the variables Fuel Price and GDP were replaced by more wide-ranging concepts, namely Price of Mobility and Economy. The purpose of the Price of Mobility macro-block is to depict the average cost of car use cost per kilometer, considering that such cost will no longer be perceived as the simple product of gasoline or diesel prices by distance traveled, but rather a compound of a series of variables that include car taxation due to environmental pressure, petro-fuel price, alternative fuel price and market share of alternative vehicles.

The macro-block Economy pretends to portray, more than the conventional stand-alone GDP growth series, an economic forecast that takes into account the performance of the economy over long periods as well as, for example, the influence of economic growth on fleet renewal rates or on the more general trends of commodity prices.

The Emissions block is intended to represent the tensions between GHG emissions and GHG emission targets. GHG emissions in transport are the consequence of the product of traffic volumes by average vehicle emissions per kilometer, which depend on the market shares of the different energy vectors in the fleet (and the age of the corresponding vehicles), whereas the GHG emission targets were set in compliance with a series of bibliography, including legal binding documents released by the European Commission [10].

From this tension between GHG gases emissions and targets will result the environmental pressure that will influence the evolution of vehicle technological standards and that will drive fiscal policies and other (regulatory) measures possibly pushing drivers to reduce car use.

Technological standards of road vehicles are treated in the Technology macro-block. This is perhaps the more complex and intricate macro-block, as it encloses within its remit a large set of variables and the interactions amongst them and with the outside blocks.

So, the Technology macro-block intents to depict the evolution of vehicle technology, both on ICE and alternative vehicles, driven by the environmental pressure due to the emission of GHG gases. This technological evolution is translated not only in lower energy consumptions but also in lower life cycle costs for both vehicle types. The alternative vehicles vector will also take into account the probable introduction of V2G systems (as an alternative fuel price depressor), the evolution on battery autonomy and on the quantity of distribution points for alternative fuels.

The pace of technological evolution for each type of vehicle is set differently, as it is considered that ICE vehicles will not experience such steep efficiency gains as alternative vehicles will, given the relative stages of maturity of these two types of vehicle traction.

At each moment in time, it is the interplay of these aspects, namely fuel costs, life cycle costs, battery autonomy, quantity of distribution points, for each type of vehicle, that determines the market competitiveness of each type of vehicle and from this we estimate their market shares in new purchases. A secondary model deals with the survival and scrappage aspects on the composition of the fleet.

Road traffic is a joint result of the Economy, the Motorization and the Price of Mobility. We have to bear in mind that traffic volume itself will be the key factor of the progression of GHG Emissions, thus closing the main internal feed-back loop of our model (Traffic > Emissions/Technology > Price of Mobility > Traffic).

<u>Implementation</u>

The actual implementation of the model was made through the use of the software VENSIM, a state-of-the-art program designed in the MIT for the development of dynamic systems. The completion of every macro-block led us to the gradual creation of about 100 different variables and auxiliary variables so we could illustrate what was felt as the correct description of this model behavior.

Following the "plausibility and humility" keywords defined above, we had to conduct a series of sensitivity tests and variable limitations with the intention of reaching a well balanced (while still illustrative of real behaviors) model. The array of variables to which elasticity of traffic volumes was highest was selected for those tests. A total of 15 main variables were retained, that we split into Established Variables or Conjectural Variables.

The Established Variables are the ones for which historical data series are available and therefore the ones with less uncertainty associated. Not surprisingly, these variables were found to be the ones already present in traditional forecasting models, i.e., variables like GDP and Motorization.

The Conjectural Variables are the ones with a higher level of uncertainty or ambiguity, with no historically observed data and therefore estimated and calibrated by us based on studied bibliography and our careful judgment. For a selected group of 10 parameters present in some of the Conjectural Variables (the ones we believe more suitable to future uncertainty), a random variation has been imposed, following a triangular distribution with mean value of 0%, maximum of 25% and minimum of -25% of the base value for each one of these parameters. Taken individually, the variation range for each of these parameters corresponds to what we regarded as a reasonable expectation considering the prevailing level of uncertainty.

With this random variation implemented, a Montecarlo Analysis with 1.000 simulations was performed— from which we took the interval between the 25th and the 75th percentiles as a window of reasonable results. The VENSIM software allows us to run this Montecarlo Analysis and extract graphical outputs for each variable, for the Base Case (without any random variation imposed) and for the outputs of the Montecarlo Analysis, represented as a percentile diagram that allows one to understand not only the opening window of results at each given moment but also where the central Base Case and the remaining outputs are positioned in relation with each other.

The following graphics show the outputs for the Base Case and for the Montecarlo Analysis, both for the output variable Traffic Volume.

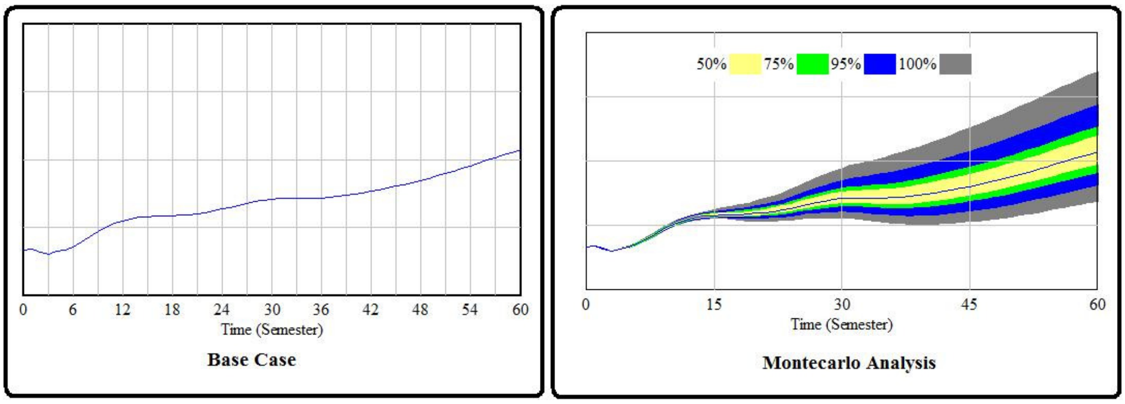

Figure 2 - Graphic Output for the Traffic Volume of the Base Case and for the Montecarlo Analysis

Conclusions

We believe our work has demonstrated that, although the traditional approach to traffic forecasting is no longer suitable for long term horizons, an alternative approach is possible providing a better insight into the range of plausible future values of traffic volumes.

Not only we were able to take into account a large set of indispensable variables that explain and drive traffic evolution, as we were also capable of successfully describing their relations and inter-dependencies with a good amount of confidence.

Furthermore, the closed form of the dynamic model provides a rather strong cross-limitation effect that leads the model to an internally balanced and reasonable evolution.

As long as we keep aware of our uncertainties and lack of exact knowledge over future happenings, we may conclude that System Dynamics appears as an excellent tool to deal with the challenges we face in this kind of exercises.

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