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Application of System Dynamics for Evaluating Truck Weight Regulations in Anhui, China ---- A Methodological Framework

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ABSTRACT

In the critical situation of prevailing overweight transportation and crag-fast enforcement in Chinese highway networks, this paper develops a methodological framework for truck weight regulation (TWR) evaluation using System Dynamics (SD). Composed of five interrelated subsystems, the framework is able to capture the highway, vehicle and freight variables that influence the effect of TWR and transportation efficiency over time. It specifically describes the development and use of the Truck Weight Regulation Evaluating Model (TWREM) for the highway freight system in Anhui province, China. Three policy alternatives are analyzed: 1) tolerant policy approach, which allows heavy-duty freight activity to continue in its current state, and is shown to lead to nearly catastrophic results; 2) rigid policy approach, which would terminate all heavy-duty freight activities immediately, and is shown to be economically infeasible; and 3) moderate policy approach, which advocates a gradual reduction of heavy-duty freight activities to a moderate state. The simulation results shows that the moderate policy approach is the most appropriate option to solve the social and economic problems arising from the activities of the heavy-duty freight transportation in Anhui. In addition, some suggestions of TWR policy in China are also made in this paper.
INTRODUCTION

Background
In China, national regulations govern the weight of trucks, buses, and trailers on highways. The regulations have important economic consequences because trucking takes up nearly three quarters of freight volume of freight transportation in China, and trucking costs are directly influenced by truck weight. Weight regulations also influence highway construction and maintenance costs, the convenience and safety of highway travel. The regulations affect inter-provincial commerce as well because the situation of highways and the needs of weight regulation for some developed provinces differ from those underdeveloped.

Since the late 1980s, the problem of overweight transportation has become increasingly seriously in China. Especially in the 21st century, as the construction of expressway sped around in China, a variety of social problems caused by heavy-duty trucks frequently became the focal concern of the public. In June, 2004, China launched a nationwide enforcement activity against overweight vehicles of which axle load or gross weight exceeds the statutory limits. By the end of 2005, the traffic management agencies have inspected and found out more than 11.69 million overweight vehicles. Of these vehicles, 3.16 million trucks were forced to unload and the unloaded goods added up to 19.19 million tons. However, for some reasons, the enforcement effect was actually unsatisfactory. The traffic management agencies found that:

✓ The overweight transportation phenomenon was still serious, especially for two-axle trucks;
✓ Due to insufficient funding and personnel, the enforcement intensity was inadequate;
✓ The enforcement intensity varied among different areas.
✓ During the law enforcement activities, not all the vehicles could be checked and there were also a few malpractices happened.
✓ The continuously rising of oil price and user tax increased the difficulty of the overweight enforcement.

In this critical situation, the World Bank brought forward the highway overweight study based on the practice of highway management in Anhui province (1). The objective is to explore the effect on the social economy which the overweight vehicles took. The study showed that heavy-duty transportation was the necessary choice in the environment of resource-intensive industries and strictly prohibiting overweight would cause the prices of many goods to rise greatly. For this reason, although large numbers of overweight trucks would damage the pavement in short order, the public and the governments across different areas showed great tolerance to overweight vehicles. At the same time, throughout its work, the research committee found that the lack of information about the exact costs and benefits of truck transportation and the impacts of the weight regulations hindered its effort to provide useful policy advice.

Literature Review
In fact, most past researches on overweight transportation has encountered the same difficulty. It is found that models and data have never been adequate for providing more than plausible indications of how institutions, markets, and technologies will react to regulatory changes, especially in the long term. Actually, responsible regulation should be a process: the regulatory authority should do the best prior analysis possible, but once regulations have been changed, the consequences must be systematically observed and adjustments made where necessary (2).

In terms of the methodologies used, most of the studies conducted by the U.S. Department of Transportation (DOT) and Transportation Research Board (TRB) over the past 20 years employed a
common five-step cost-benefit analysis (CBA) method (3)(4)(5). This standard framework is a necessary starting point for evaluation of changes in weight regulations. However, within this benefit–cost framework, the outstanding DOT (2000) Comprehensive Truck Size and Weight Study, as well as most of its predecessors, is constrained by the following weaknesses:

1) Too strong assumptions about the scope of policy changes to be considered. Instead of serving as problem-solving exercises—asking how the weight regulations can be used as part of a strategy for increasing the benefits of the highway system—evaluations often have appeared directionless, asking instead what would happen if a specific limit were incrementally changed or if a particular industry proposal was put into effect. In contrast, solving the problem of maximizing highway benefits requires starting with a trial solution, discovering its shortcomings through initial evaluation, and then refining the proposal to overcome the shortcomings and come closer to a satisfactory solution. This iterative process, if not entirely lacking in past studies, has seldom been explicit or systematic (6).

2) Because the relationships between components of highway transportation system have feedback characteristics reciprocally, the system response seems to be counterintuitive. The method of CBA cannot be used to handle these feedbacks effectively, not to mention analyzing the self-adaptive or self-organized characteristics of social economy systems.

3) CBA can only be used to analyze the “instantaneous” change of social economy system when the vehicle weight regulation changes. It is not sufficient without considering the dynamic course of system evolution in the long term, because the results obtained from the static analysis sometimes seems to be one-sided or casual.

4) CBA needs a lot of input data. Obtaining those data is costly and this considerably limits the wide application of CBA.

In a word, the limitations cited above have restricted the use of this classical framework, especially in those developing countries or areas.

**Methodology Development**

It is well known that truck weight regulations are a mechanism for balancing the potential public costs of truck travel against the benefits of lower shipper and carrier costs for freight transportation. The most useful weight study would be a structured search for better means of attaining these goals. These means might entail changes in truck weight regulations coordinated with changes in design and maintenance of pavement and bridges, highway tolls, driver regulations related to safety, or other aspects of highway management.

Compared to the CBA, the System Dynamics (SD) methods can be used to simulate the complicated feedback social system, in which the human judgment, experience and logics are combined so that the problem involving evaluating truck weight regulation can be effectively solved. From a practical business perspective, Lyneis (2000) recommended the use of the System Dynamics models to “forecast” the behavior of markets (7). He claimed that the structural orientation of the SD models provides more accurate descriptions of short and mid-term behavior than statistical models, which often become skewed by “noise” in the system. He also claimed that the SD models can be used not only for decision-making, but also for identifying variables in a system that have the greatest impact on the decision-making and deserve the most attention over time. In the domain of truck weight regulation evaluation, Lyneis’ market perspective of SD makes it a useful tool for decision-makers to make TWR decisions based on their interpretation of the past and present behavior of the system.

In brief, the elemental building blocks of SD model are consisted of *stocks, flows, converters,* and
feedback loops, as shown in Figure 1 (8). Stock represents accumulations of some measurable entity, for example, people, parts, money, or even intangibles such as happiness. Flow is the physical or conceptual entities in systems that move over time. Flows got into or out of stocks cause them to change. Converter helps to describe the flow and serve as a tool to calculate system performance metrics (9). Feedback occurs in a system when its own past activity influences its future (2). In the system feedback networks, stocks and flows virtually ensure that a dynamic system will behave in a difficult-to-understand or counterintuitive way. As a result, system dynamics modeling involves the identification, mapping-out, and simulation of a system's stocks, flows, converter, and feedback loops.

![Figure 1 Example of a Simple System Dynamics Stock-Flow-Feedback Loop Structure](image)

Generally speaking, researches on truck weight regulations evaluation involved three different levels of investigation: theoretical evaluations, model development and model applications. Part of the research is presented in this study, especially a contribution to the aspect of development through applying System Dynamics Modeling technique to deal with the problems of evaluating truck weight regulations. It first describes of the model framework, followed by model development and validation processes. The validated model is then used to simulate the existing overweight problems in Anhui province. The simulation results and recommendations for policy implementation are also discussed.

PROPOSED FRAMEWORK

The social impacts of truck weight regulations contain many aspects, such as level of service (LOS) of highways, traffic safety, environment, commodity circulation, vehicle management and so on. Current weight regulation analysis models used to address these issues are either based solely upon empirical formulations or limited to application of only part of the problem. A fundamentally sound and integrated framework of interrelated models that is capable of simulating the real behavior of the highway transportation system and one that incorporates almost all significant influencing factors, is therefore greatly needed.

Considering the fact that study on truck weight regulation is one of the largest research projects, the development of Truck Weight Regulation Evaluating Model (TWREM) can be divided into several phases. This paper discusses the structure of the phase I of TWREM, including a general introduction to the basal model structure that comprises the variables of the freight demand forecasting, trucking cost, truck fleet evolution, truck usage, and pavement performance subsystems. Figure 2 shows the basic building blocks of the modeling exercise. It depicts the flow of material and information in the feedback systems of the five subsystems.

The input variables of system include: 1) traffic variables, such as traffic volume and axle-load distribution; 2) transportation cost variables, such as fuel price, transportation tax, vehicle maintenance cost...
and so on; 3) road variables, such as pavement thickness, designed deflection, pavement width and so on. The output variables of system include freight volume, freight turnover, total freight cost, equivalent single axle loads (ESALs), pavement evenness, pavement maintenance cost, and so on. In addition, the output variables can be added or cut down conveniently.

![Diagram](image.png)

**FIGURE 2 Structural components of the Truck Weight Regulation Evaluating Model**

The framework is designed in an open and flexible manner such that future expansion is very easy. On-going projects will be continued through completion and additional subsystems such as environment subsystem, traffic safety subsystem, bridge impact subsystem and enforcement cost subsystem will be integrated for continuation through other ongoing programs.

**MODEL DEVELOPMENT**

**Freight Demand Forecasting Subsystem (FDFS)**

The function of FDFS is to forecast the annual freight demand in the future according to vehicle transportation cost exported from trucking cost subsystem and the development of external social economy. Considering that shipment size is one of the most important attributes of the freight demand and it is
directly connected with truck’s loadage (10), the freight demand in the subsystem and the other subsystems uses the distribution value (e.g., not total value or mean value) of every shipment size to express the freight demand and freight volume. In FDFS, the freight demand of different shipment sizes will be forecasted separately.

FDFS consists of three model sets that are uniquely integrated: a primary freight demand model set, a demand growth model set, and a demand fluctuating model set, as shown in Figure 3. From the base year, the freight volume of each shipment size increases at some “natural rate” from the demand growth model set which reflects the increasing need for freight generated by increasing regional population and economy. In the circumstances of changeless industry structure, the increasing rates of each shipment size are the same, but on the condition that the industry structure changes, for example, when the industry structure is in the transition from resource-intensive to capital-intensive, the increasing rates of small shipment sizes are higher than those of large shipment sizes. At the same time, transportation cost, which is one of the freight supply attributes, has influence on the freight transportation demand and places a premium on or restrains the demand of natural freight. Supposing the profit rate is fixed and the price elasticity equals to the cost elasticity, according to the cost elasticity of freight demand and changes of freight cost, parts of freight demand are induced or diverted (11). Finally, the freight demand of each shipment size can be obtained. The exogenous variables of FDFS include cost elasticity of different shipment size, population and economy with their variety. The endogenous variables are the transportation cost of each shipment size or truck loadage.

FIGURE 3 Generic representation of FDFS
**Trucking Cost Subsystem (TCS)**

The function of TCS is to calculate the unit transportation cost of every truck loadage (weight of cargo) level or shipment size. The subsystem has two parts: one is the cost calculating model, and the other is cost function model. As the loadage of certain truck is not fixed and the cost data is insufficient to calculate the transportation cost of each shipment size/truck loadage credibly, a simplified method is developed which only investigates the vehicles with loadage near the peak loadage of truck loadage distribution, namely, the “optimal loadage”. The distribution in the base year can be obtained from truck weight survey. In the cost calculating model, the unit freight cost can be calculated based on those cost payouts. Then, the cost function model generates the freight cost function according to the optimal loadage and the unit freight cost of all truck types. A generic representation of such a subsystem is shown in Figure 4. The exogenous variables, namely the influence factors of vehicle cost, include the price of factors of production (fuel, tire, labor and so on), tax, and expecting fine/punishment. The endogenous variables consist of the optimal loadage and the pavement evenness which comes from pavement performance subsystem. The output variables are variable cost and fixed cost of each truck type, the freight cost function applicable for all truck types, and so on.

![FIGURE 4 Generic representation of TCS](image)

**Truck Usage Subsystem (TUS)**

The function of TUS is to analyze the truck loadage decision and the truck type choosing behavior of truck users under the influence of exogenous factors. These factors include truck weight regulation, tax, fine and the price of factors of production. The subsystem contains a loadage decision model and a truck type/modal split model. The exogenous variables consist of truck weight regulation and user preference. The endogenous variables are fixed cost and variable cost of each truck type. The output variables consist of
optimal loadage of each truck type and the truck type split proportion of each shipment size. A generic representation of such a sub-system is shown in Figure 5.

Referring to the theories of transportation economics, the truck’s optimal loadage can be estimated using concepts of fixed cost and variable cost which are close to proxy variables herein. If the calculated optimal loadage of certain truck type exceeds the statutory limits, then the latter should be the actual optimal loadage instead. The split proportion of truck type of each shipment size is calculated using nest-logit model (12). The main impact factors of user’s utility consist of unit freight cost, statutory limit, market risk and user’s preference.

**Truck Fleet Evolution Subsystem (TFES)**

The function of TFES is to forecast the dynamic change of the amount of each truck type. It contains vehicle replacing model, vehicle purchasing model and truck amount forecasting model. The exogenous variables consist of vehicle age distribution of each truck type and user’s preference of purchasing trucks. The endogenous variables are freight demand of each shipment size and optimal loadage of each truck type. The output variables are amount of each truck type, realizable freight volume, and amount of operational trucks corresponding to each shipment size. A generic representation of TFES is shown in Figure 6.

The number of certain vehicle type is determined by the number of vehicle replaced and the number of vehicle purchased. The main impact factors of vehicle replacing include “natural replacing factor” derived from the vehicle age distribution and the optimal loadage using economy life theory, and “artificial replacing factor” which reflects the difference of market demand on certain truck type. The vehicle purchasing behavior is mainly dominated by freight supply-demand relationship and user’s preference. It is assumed that if the total demand of a certain vehicle type exceeds the actual vehicle amount, actual freight volume will decrease accordingly because the supply is not enough, and if the total demand of a certain vehicle type is less than the actual vehicle amount, part of the vehicles will be left unused.
It is important that the stock type of vehicle amount of each age group used in TFES should be “conveyor” to simulate the process that vehicle age increases from year to year. After a simulation interval (one year), except for the either naturally or artificially replaced vehicles, the remaining vehicles will be moved to the next vehicle age group in turn till all old vehicles are replaced due to vehicle life limit.

**Pavement Performance Subsystem (PPS)**

The function of PPS is to forecast the deterioration process of pavement performance in the circumstance of certain truck traffic with their weight distribution. The subsystem is composed of ESALs calculating model, pavement maintenance decision model and pavement performance forecasting model. The exogenous variables include: 1) initial pavement parameters such as mileage, pavement width, initial deflection, pavement type, pavement thickness and so on; 2) other impact factors such as temperature, humidity and so on; 3) and pavement maintenance decision parameters such as maintenance interval and performance threshold of maintenance. The endogenous variables are truck traffic volume transformed from amount of operational trucks exported from TFES and the truck loadage distribution exported from TFES. The output variables are International Roughness Index (IRI) and pavement maintenance cost. A generic representation of such a sub-system is illustrated in Figure 7.
First, the truck loadage is translated into gross truck weight using experimental formula, and the gross truck weight is translated into axle weight of each axle group using Weight Split Factor. In succession, probability ESALs of single truck and annual cumulative ESALs of all trucks can be calculated using traditional truck-pavement mechanical formula. In the following, the value of Riding Quality Index (RQI) and IRI can be forecasted using certain pavement deterioration formula. When RQI is smaller than threshold value of pavement performance or the pavement age reaches certain value, pavement needs to be maintained and the IRI is set to the initial value.

**DATA ACQUISITION AND MODEL VALIDATION**

In building this model, hypotheses of the system were formulated and transformed into model equations using the DYNAMO programming language (13) with data and information from the highway systems of Anhui province. One of the major difficulties encountered during the process was the availability of data. This model is based on both primary data from onsite survey and secondary existing data. The main sources of secondary data and information are the Anhui Statistical Yearbook (14) (15). The primary data were investigated, measurements, observations, interviews and through visits to the related areas over a certain period of time. The structure of this model was first developed for the Hefei-Luan highway system in Anhui, and was later applied to three other highway systems. Some parameters used in the model are shown in Table 1.
TABLE 1 Some parameters used in the SD model of the Anhui highways

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Average Daily Traffic of SU2*</td>
<td>2265 (vehicle)</td>
</tr>
<tr>
<td>Annual Average Daily Traffic of S112*</td>
<td>501 (vehicle)</td>
</tr>
<tr>
<td>Peak loadage of SU2</td>
<td>18.00 (ton)</td>
</tr>
<tr>
<td>Peak loadage of S112</td>
<td>34.01 (ton)</td>
</tr>
<tr>
<td>Price of diesel oil</td>
<td>3.25 (Yuan/liter)</td>
</tr>
<tr>
<td>Road Length</td>
<td>250 (km)</td>
</tr>
<tr>
<td>Road width</td>
<td>22.5 (m)</td>
</tr>
<tr>
<td>Pavement thickness</td>
<td>15 (cm)</td>
</tr>
</tbody>
</table>

* SU2 means the single unit truck with two axles; S112 means the semi-trailer with one steering axle, one driving axle and tandem rear-axle.

The data in the table were obtained from sources already referenced and were used in the TWRE model in World Bank’s overloading study report (1) (16). After the model was developed, simulation runs were conducted over the historical periods of the highway operations. The freight volume outputs simulated by the model were compared to the actual value of the highway over the same period. A highly significant correlation was found between the simulated data and the actual data. This validation process was undertaken for other variables such as “truck traffic”, “freight turnover” and “IRI”, and the results have satisfying correlation with the actual system. Figure 8 shows a typical result for freight volume.

FIGURE 8 Comparison of TWREM Predicted Freight Volume and Actual Measurements

POLICY FORMULATION
Policy formulation is a process through which adequate alternative Truck Weight Regulation policies for a system are developed based on the failures and problems of existing policies. The developed model is to
simulate these alternative policies with different parameter and structures. The evaluation of each alternative policy will be based on the following criteria:

- Its capability to stimulate the development of economy;
- Its capability to maintain the favorable pavement performance of highways;
- Its capability to reduce freight cost and to improve freight efficiency;
- Its capability to avoid convulsions; and
- Its effects on enforcement feasibility.

Three alternative policies are evaluated here using the model within the framework of the above criteria. These policies are "Tolerant" policy, “Rigid” policy and “Moderate” policy.

The Tolerant Policy
The tolerant policy approach approximates the current practice employed by the highway management authorities in Anhui. Although highway management authorities placed much emphasis on pavement protection, the heavy duty trucks are inadequately monitored and fined and consequently the effect of pavement protection is limited. The results of these policies were simulated in the model by making the following adjustments:

- An “economical limit” was used in place of the truck weight limit; and
- The fine for trucks is supposed to be ubiquitously high as practice.

The Rigid Policy
The rigid approach would terminate all heavy-duty transportation activities immediately, as exhibited during the overweight enforcement activity in 2004. The following changes are made to the model:

- The truck weight limit equals to existing statutory limit;
- The fine for trucks varies with their probabilistic overweight loadage; and
- Highway toll for truck type S112 is reduced by twenty percent.

The Moderate Policy
The moderate approach strikes a compromise between the “tolerant” and the “rigid” approaches in an attempt to avoid turbulence of regional markets. The original model is adjusted as follows:

- The truck weight limit equals to the middle value between the “economical limit” and the existed statutory limit, in other words, the statutory limit is increased;
- The fine for trucks varies with their probabilistic overweight loadage.

ANALYSES AND DISCUSSIONS
Based on the practice of Anhui province, SU2 and S112 are chosen as the representative truck types in simulation analysis, the interval of discrete shipment size and axle-load distribution are initialized to be 4 tons, and the simulation periods is 20 years. Some of the important results produced by the TWREM are:

- Rigid policy will cause mutation of truck type configuration. As shown in Figure 9, S112 will become the primary truck type abruptly instead of the currently prevailing SU2 trucks. The forecasting trend is validated by the practice at the overweight enforcement period in Anhui.
- Rigid policy and moderate policy will reduce the heavy-duty truck’s loadage and the ESALs per vehicle. The annual cumulative ESALs of truck traffic will be kept within 3,000 times per day under the rigid policy. However, this value will exceed 20,000 times per day or even more under the tolerant
policy. Obviously, more rigid TWR policy will greatly protect the pavement maintenance from tremendous axle loads and the tolerant policy will lead to catastrophic results on highway networks.

![Graph 1: Page 2](image1)

![Graph 1: Page 3](image2)

FIGURE 9 Effects of three policies approach on truck traffic

On the other hand, too rigid policy will have adverse impacts on freight transportation. The simulation result shows that in the first two or three years, the freight volume drops rapidly. This is because the truck type configuration and load capacity become out of line with the freight demand under loadage enforcement abruptly and adjustment of truck type evolution or truck loadage both need a certain period of time. At the same time, rigid policy counteracts the scale economy in freight transportation got from higher truck loadage and results in the increase of freight cost. As shown in Figure 10, the average freight cost, namely total freight cost divided by total freight turnover, exceeds 0.34 Yuan per ton per kilometer
increasingly under rigid policy, but it never reaches 0.32 Yuan per ton per kilometer under moderate policy or tolerant policy. Especially in the initial stage of enforcement, this difference is so significant as to overstep the receptivity of social economy.

The simulation result indicates that the more rigid the TWR policy is, the more highway profit there will be. Here the highway profit refers to the revenues got from truck owners minus maintenance cost of pavement. The profit will be obtained by the highway operators in the long run because of the cost saving from pavement maintenance. But in short term, this benefit seems negligible compared with substantive enforcement cost of TWR. Therefore, the highway operator may not be desirous of supporting rigid policy for the sake of negligible or even negative short-term benefit.

**FIGURE 10 Effects of three policies approach on freight/social cost indices**

*Graph 1: Page 4*

*Graph 1: Page 5*
If the local government can be viewed as a “super decision-maker” and he will choose the policy achieving best freight efficiency of the whole society. Considering the benefits of highway operators, truck owners and customers, the average social cost, namely sum of total freight cost plus pavement maintenance cost divided by total freight turnover, may be an alternative decision index. The lower the average social cost is, the more efficient the social freight system will be. As we can see in Figure 9, instead of the trendy rigid policy in China, the moderate policy seems to be the best choice for the super decision-maker. It offers an explanation why some local governments in Anhui province are not interested in the long-term of TWR enforcement.

Some useful conclusions can be drawn from the truck weight regulation policy simulation: 1) the truck weight limit is one of the key variables which influence the effect of TWR and transportation efficiency; 2) in China, specifically in the provinces where the leading industry is resource-intensive, the government should choose the “moderate” policy for managing heavy-duty trucks instead of “rigid” policy to minimize the social impacts on freight transportation and commodity circulation by truck weight regulation tempestuously; and 3) the foundation of these TWR policies is the effective and fair enforcement which is still the weakness of transportation management in China.

CONCLUSIONS

The main objective of this study is to develop a simulation model for evaluating different management policies for heavy-duty vehicles transportation. It shows how the development and use of computer modeling using the Truck Weight Regulation Evaluating Model (TWREM) can give insights into the highway freight system of Anhui province. During the construction phase of the model, data and information were obtained from the Anhui Provincial Communications Department (APCD). The ‘Moderate Policy’ approach derived from the incorporated modeling is shown to be the most appropriate option to solve the social and economic problems arising from the activities of the heavy-duty transportation. Although the model has been developed and validated for the Anhui highway system, it has been designed in an open and flexible manner and could be applied to other areas or countries as well by appropriately changing in the values of the parameters and constants. It can also be reduced or increased in size according to the research objective. It is expected that the results of this study will contribute to the development and implementation of truck weight regulation policies.

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