Existing Design Processes in New Mexico and PR China in Comparison to System Engineering for Transportation (SET) Concepts

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Abstract

Application of Systems Engineering for Transportation to a specific pavement performance problem is compared to existing approaches used in the State of New Mexico/USA and Ministry of Communications/People's Republic of China. The advantages of the comprehensive approach to transportation are clear, however, the application in real projects is directly affected by the availability of the necessary information and personnel with skills required to properly execute the SET approach. Better information systems for use with SET are essential. Training of specialists in areas new to them will be of great importance to facilitate a balanced consideration of all important aspects of a project.

Introduction

Simultaneous Vehicle and Infrastructure Analysis (SVIA) and Simultaneous Vehicle and Infrastructure Design (SVID) have been developed conceptually and are now integrated as Systems Engineering for Transportation (SET). The present paper offers an evaluation of this concept, applied to a specific project, in comparison to existing development/design processes used in the State of New Mexico, United States of America and in the Ministry of Communications, People's Republic of China. For brevity in this discussion the organizations are identified by acronyms shown in Table 1. An example project concerns the rehabilitation of highway pavement that are presently exhibiting unacceptable roughness. In the specific example all elements of the SET Wheel are not involved as discussed below. The results will be discussed to further understanding of the SET concept.

Table 1—Organization Identifications Used.

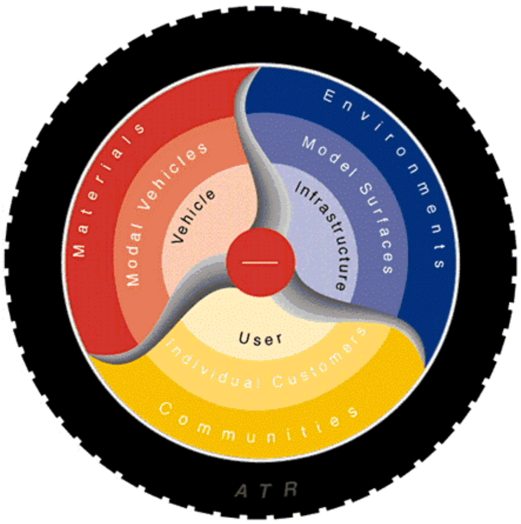
Organization—PR China	Organization—NM/USA
PCD—Provincial Communication Dept.	NMSHTD—State Dept. of Transportation
	DE—District Engineer
PPC—Provincial Planning Committee	PD—Planning Division
	DD—Design Division
	MLB—Materials Lab Bureau
MOC—Ministry of Communications	FHWA—Federal Highway administration
SPC—National State Planning Commission	USDOT—United States Dept of Transportation

SVIA/SVID/SET

SVIA is a systems approach to integrate that which is known about the transportation event under study. It has two focal points, that which is known and probable causes and other possibilities.

Three elements of the transportation system are considered, they are the vehicle, infrastructure, and user. The SET Wheel is used as a framework for representing the transportation system. The wheel is divided equally into three segments representing the three elements. These three segments are then intersected by concentric circles representing the specific subject of interest (innermost circle), the types of subjects and their function (second circle), and the environment in which the types exist (outer circle). The SET Wheel is shown in Figure 1.

Figure 1. SET Wheel.



The wheel is extended vertically into a cylinder with top and bottom circles. In SVIA the top represents what is known about the situation under study while the bottom circle represents probable causes and other possibilities. From these two planes a third may be developed that represents hypotheses or proposed models for further investigation of the project of interest.

SVID builds on the SET framework and capabilities developed in SVIA. It extends the capability from examination of the past to objectives for the future. While SVIA is the connecting link between observed past and present, SVID is the connecting link between the present and future objectives. It presently consists of an eight step process. The required activities are: (1) state the design objective; (2) understand current design (3) propose alternative designs; (4) assess alternative designs; (5) select potential design; (6) simultaneous design; (7) decision to implement; (8) project management; (9) project evaluation.

Existing Design/Development Processes

The New Mexico State Highway and Transportation Department (NMSHTD), USA and Ministry of Communications (MOC), People's Republic of China perform similar tasks in regard to design and development of projects. These processes are compared in Table 2. The steps in the processes are similar with the exception that public involvement and environmental review are explicitly required in the NMSHTD process.

Application of SET

In the present paper a specific project will be analyzed using simultaneous vehicle infrastructure analysis (SVIA) and then a design will be developed using simultaneous vehicle infrastructure design (SVID). These processes will be compared to existing methods. The project is an interchange located at milepost 149 on Interstate Highway 40 (I40) where it crosses Paseo del Volcan and Central Avenue, near Albuquerque, New Mexico, USA. This includes on/off ramps for both directions of travel, a bridge and connecting roadways. The reason the project was selected for this paper is that the pavement on the westbound off ramp and the connecting road the south frontage road exhibits severe roughness due to instability and shoving of the surface layer. The objective of the project is to select a rehabilitation alternative.

Table 2. NM/MOC Comparison of Tasks.

Tasks	MOC, PR China	NMSHTD/USA
Need for the project	PCD/PPC/MOC/SPC	District Planning Division
Scoping/Feasibility	PCD/PPC	DE
Proj. Establishment/Scoping	PCD/PPC/MOC/SPD	PD
Environmental Assessment	No Specific Requirements	PD
Drainage design	PCD/HPDI	DD
Alignment design	PCD/HPDI	DD
Geotechnical invest.	PCD/HPDI	MLB
Pavement design	PCD/HPDI	MLB
Property surveyPCD	DD	
Bridge designPCD	BD/HPDI	
Grading & drainage	PCD/HPDI	DD
Plan in handPCD/MOC/SPC		DD./FHWA
Plans, specifications & estimate	PCD	DD
Advertise for bids	PCD	Procurement
Receive bids, select contractor	PCD	Procurement
Construction	PCD	CD

SVIA-Simultaneous Vehicle Infrastructure Analysis.

Vehicles

When the project was initiated it was believed the distress was a direct result of heavy truck traffic that accompanied opening of the Cerro Colorado Landfill just west of the site in 1991. In this analysis it was discovered that heavy vehicles using the interchange are refuse trucks (several types), freight trucks (several types) and smaller, primarily four-wheeled vehicles. New Mexico State limits on axle loads which apply to heavy trucks are shown in Table 3. The MOC has less formal axle load limits and designs for heaviest vehicle loads.

Table 3—New Mexico Axle Load Limits.

Category of Load	Maximum Allowable Load kg (lbs.)
single axle weight	9798 (21600)
tandem axle weight	15567 (34320)
vehicle gross weight (5 axle)	34013 (75000)
vehicle gross weight (other)	39190 (86400)

On the basis of state limits the refuse trucks may legally carry 15567 kg. (34320 lb.) on the rear tandem axle. Front axles are typically 4535 kg. (10000 lb.) although the actual load is not known at this time. This estimate yields a gross vehicle weight of 20103 kg.(44320 lb.) maximum allowable.

Typical refuse trucks have a capacity for 29 m^3 (38 yd^3) of waste. Municipal solid waste weighs between 178 and 450 kg./m^3 (300 and 760 lb./yd^3) resulting in a payload of 5170 to 13063 kg. (11400 to 28800 lb.). No directly measured vehicle weights were available.

Most freight trucking companies operate five axle single trailer (1 single axle, 2 tandem axles) or five axle two-trailer (5 single axles) combinations for freight in New Mexico. Maximum allowable gross weights are 35670 kg. (78640 lb.) and 43726 kg.(96400 lb.) respectively. It has recently become common with some trailer manufacturers to separate the rear tandem axle forming two single axles. If this is done the single trailer maximum load is raised to 39698 kg. (87520 lb.).

Traffic estimates in 1992 indicated average annual daily traffic (AADT) on the westbound off-ramp of 1315 with 10 percent trucks. Using a truck factor of 1 equivalent single wheel load per truck yields a 20 year total of 960,600 ESALs during the life of the pavement.

Infrastructure

The interchange was designed in 1968 and construction followed in the early 1970s. The facility is about 26 years of age. The focus of this paper is the pavement, described in Table 4 below. The landfill opened in 1991. In 1992 the pavement surface was overlaid by placing a 50 mm (2 in.) asphalt concrete surface to protect the underlying pavement. Apparently this was done because the existing surface was deteriorated due to alkali-silica reactivity in the concrete. The overlay has shoved in all locations where braking or turning of the trucks occurs. On some parts of the westbound off-ramp the concrete surface is exposed where the overlay is completely removed. Severe roughness is due to surface uneveness from shoving. This is severe at the stop sign on the westbound off-ramp at Paseo del Volcan and at the stop sign for southbound Paseo del Volcan at Central Avenue.

The existing infrastructure are the components of the highway interchange at Exit 149 on I40, west of Albuquerque. This includes (1) the west bound off-ramp, (2) the east bound on-ramp, (3) the bridge, (4) portions of Paseo del Volcan and (5) the frontage road to the Cerro Colorado Landfill. Table 4 shows design and condition information for the interchange.

Table 4—Data on the Paseo del Volcan/ I40 Interchange.

Speed	Design = 70	Posted (Nov. 1997) = 65		*I40 Mainlanes
	Design = 45	Posted (Nov. 1997) = 35		*Paseo del Volcan
Design Traffic:				
Volume	ADT (1962)	4953	Heavy Comm. 10%	
	ADT (1975)	13,272	Heavy Comm. 9%	DHV 1,593
	AADT (1992)	WB Off =1423, On = 1315/ EB Off = 933, On = 1533		
Pavement Design:				
	ADL (rigid) = 932.8 (1968—1988, 20 year design, 6.8 million ESALs)			
	ADL (flex.) = 876.8 (94% in right lane, 20 year design, 6.4 million ESALs)			
Pavement Thickness:				
WB off ramp/EB on ramp: 200 mm (8 in.) PCC, 100 mm (4 in.) CTB, Class B				
SB frontage road: 16 mm (5/8 in.) ST, 50 mm (2 in.) HMA, 150 mm (6 in.) BC, R-Value = 30				
Maintenance: In 1992 a 50 mm (2 in.) Asphalt concrete overlay was placed				
Condition:				
	Off-ramp overlay has shoved severely at braking and or turning locations			
	In several areas the underlying PCC is exposed, there is map cracking distress, typical of that due to alkali-silica reactivity (ASR).			
	Paseo del Volcan at the stop sign for Central Avenue has severe shoving distress.			
	Pavement on northbound Paseo del Volcan at Central Avenue, moderate shoving.			

Other pavements are generally in good condition, no signs of structural distress.

Users.

Much of the area surrounding this interchange is unoccupied, roughly 10 percent is built out in 1997. Significant development in the area involves trucking related activities: (1) in 1991 the City of Albuquerque opened the Cerro Colorado Landfill, west of the interchange along the south frontage road, virtually all of the refuse trucks exit I40 at Paseo del Volcan; (2) in 1995, Roadrunner Trucking constructed a 3345 m^2 (36,000 $ft.^2$) combination office and truck terminal on a site along the north side of Central Avenue, 0.8 km (0.5 mi.) east of Paseo del Volcan; (3) in 1996 an auctioneer's warehouse was built by Forke Brothers Auctioneers along the south side of I40 frontage road just west of the I40/Central/Paseo del Volcan intersection; (4) in 1996 Freightliner's Inc. built a truck service warehouse within the northwest quadrant of the intersection, along the west side of Paseo del Volcan; (5) in 1995 at the intersection of Central Avenue and Paseo del Volcan, a truck terminal facility was opened by Conway Western Express, and (6) a number of residential areas have access from this interchange.

The SVIA process includes consideration of the causes for the present condition. From the above information there are three aspects that standout as important in this respect. First, the truck traffic actually experienced is dramatically greater than considered in design. All pavements are beyond the twenty year design life used for the original design by NMSHTD. Second, alkali-silica reactivity has damaged the concrete pavement prematurely. ASR is a destructive chemical reaction between the alkaline components of Portland cement, reactive silica in aggregates when combined with water. The extent of this damage is not known. Third, an asphalt overlay was placed over the existing pavement, under heavy truck traffic and has exhibited inadequate stability. Experience has indicated asphalt overlays do not perform well under braking and turning of truck traffic.

SVID-Simultaneous Vehicle Infrastructure Design

The design objective is to provide a surface that is acceptable from a roughness standpoint. At present the pavement is beyond it's design life and is not performing acceptably. This is due to damage from ASR and from inadequate stability in the overlay mix that was placed in 1992. Two problems with the original design are apparent: (1) a concrete mix that is susceptible to ASR and (2) an asphalt overlay that is not stable under the existing traffic.

In order to propose alternate designs it is essential obtain current estimates of loads for the pavement design. There are two issues that are involved. First is an accurate count of the actual loads being applied to the pavement. Both the magnitude and the number of loads are needed. In the time frame of this project those data were not available. Second, is a more fundamental issue of what load characteristics should be considered for pavement design. It appears the major problems are not related to the structural capacity of the pavements, but the stability of the surface mixture. This suggests special consideration is needed for locations with heavy vehicles braking and turning. Some method of estimating the actual dynamic loads applied to the pavement surface is needed. This does not presently exist.

Vehicles

One alternative design is to route truck traffic away from this interchange. Current designs for trucks in the US include some sort of air suspension system. These are of two types, Henricksen and air-ride suspension systems. The first, is a non-adjustable system while the second is adjustable to some extent. However, most users do not adjust the suspension once it is set-up. These systems are commercially available and it is not possible to implement other systems because they are not commercially available.

Smart suspension systems are presently being investigated in research and may offer improvements in the load characteristics for both the vehicle and the pavement surface. Active systems vary the stiffness of the suspension based on measured responses of the vehicle to the surface on which it is traveling. Using SVID it is desirable to formulate a method of estimating future directions in vehicle technology in order to include these developments in design considerations.

Infrastructure

The current pavement is beyond it's design life and the concrete material is damaged due to ASR. Reconstruction should be considered as one alternative. Another alternate that should be considered is rehabilitation of the existing surface since there appears to be no structural distress. This involves structural load testing of the existing pavement to verify load capacity. Once the load capacity is verified, special asphalt concrete mixture designs developed for heavy traffic areas (such as bus stops) should be considered for use. Asphalt mix stability is a common problem at intersections and bus stops with shoving distress frequent in and around the city.

A third alternative is to overlay the existing pavement with a new Portland cement concrete surface. In order to do this the existing asphalt overlay and deteriorated portion of the concrete must be milled off the existing surface. PCC overlays are normally not placed on deteriorated surfaces. Since the existing surface exhibits distress from alkali-silica reactivity, some part of the surface should be removed to expose solid material. Testing of the pavement is needed to establish the depth of deteriorated concrete in order to select the milling depth.

Users

Maintenance personnel may be able to perform interim work on the surface to improve its present condition. This may involve patching the existing overlay material, or milling the material to remove the worst portions of uneveness in the surface.

The planning, design, construction and maintenance personnel should study this specific site in enough detail to understand the type of loads applied to the pavement, the construction methods and materials used for the overlay and the nature of the resulting failure. Proper training in condition survey procedures is essential for maintenance personnel to investigate and to identify causes for pavement deterioration. In addition, this kind of event, a pavement failure, needs to be communicated to other staff (planners, designers, construction, etc.) in order to educate as many people as possible through this experience.

Implementation Issues in PR China and NM/USA

With the continuously prospering national economy producing an annual growth rate of more than 10% in PR China, the three elements identified in the SET wheel (infrastructure, vehicle and users) are changing rapidly. The number of privately owned vehicles has grown by 1 million, or 15% annually since 1990. The total number reached 11 million by the end of 1996, which was more than twice the 1990 level. In the national ninth five-year-plan, the SPC included the construction of 130,000 km. (80,800 mi.) of new roads by the year 2000. By then the current road network will extend to 1.3 million km. (0.81 million mi.) The MOC also planned to finish the National Trunk Highway System by 2000 with the increased length of 8600 km. (5343 mi.). By the year 2010, the total mileage of the national highway network will reach 35,000 km. (21,750 mi.). The major highway network in New Mexico is established and major effort is now directed to maintaining and rehabilitating the existing system of about 26,450 km. (12,000 mi.)

Facing accelerating transportation demands, there are compelling reasons for China to redefine the framework and tools of the transportation system as a whole. While a developed country like the USA is focusing on equity, accessibility, environmental responsibility, and sustainability of the highway system, achieving economic development and competitiveness, as well as providing incentives and improving the environment for the automobile industry are a major concerns to Chinese transportation administrators. However, both countries will confront the same issues in improving the transportation services. It is believed that the approaches and technologies to address these problems will converge to the same answers which may be generalized worldwide.

When SVID, as a part of the SET was first introduced in China in 1996, it aroused broad attention of Chinese transportation practitioners. With a follow up Sino-American seminar on "SVID in China" held in May, 1997, constructive dialogues and exploration of its potential applications have been achieved between the counterparts of these two countries. However, as Mr. David Albright pointed out in his first paper about SVID, " the simplicity of SVID is both its strength and weakness." Its strength lies in people's ability to understand the concept immediately. Any professional or even nonprofessional who realizes the inappropriate separation of the infrastructure and vehicle would appreciate the value of SVID. However, the complexity of utilizing this concept behind the simplicity and the functional segregation of the infrastructure sector and the vehicle sector often turn it into an ideal but unreachable goal. One of the major purposes of this paper is to show that SET is applicable to all participants in the system. Indeed in the US the manufacturers and operators of vehicles are completed separate from infrastructure organizations, communication will be a major obstacle.

The project in NM discussed above features age exceeding the design life, under estimated traffic volume, unplanned increase in heavy vehicles, pavement deterioration due to ASR, and the present need for rehabilitation or reconstruction to restore functionality. Within the current Chinese road network, similar projects exist all across the country. The Chinese road designers, constructors and maintenance people have to solve the same problems faced by NMSHTD. After comparing the highway design and development processes as well as the major tasks between PR China and NM/USA, it is found that there are distinct differences existing in the project initiation and approval phases. The engineering design and construction activities, however, are very similar. After the analysis of the project by SVIA, the proposed alternatives obtained through SVID are very likely to agree with recommendation by Chinese engineers. However, under the specific political, cultural, and social environment, the final design chosen by the Chinese highway managers from the similar alternatives may not be the same as that selected by the NMSHTD.

The project in NM/USA needs to select a rehabilitation or reconstruction plan. However, the advantages of SET should not be limited to finding the solutions for the current problems or applied only by the front-line people. The earlier utilization of SET in the system and the higher level at which SET is implemented, the more benefit will be achieved through design-in quality and preventive measures.

In the central planning Chinese government system, SPC and MOC bear the responsibilities to manage the national transportation system in a macro manner. SPC also plays a major role in setting up the pace and direction of the automobile industry. Hence, the most effective and efficient way of realizing the value of SET at the national level might call for SPC, as the highest planning authority, to integrate the development of infrastructure and vehicle. Establishing commitments to a systematic approach and optimization at the top is likely to guarantee the expected results by filtering this concept through the hierarchical bureaucracy system in China. Similarly, At the provincial and municipal levels, SET should be applied by the PPC and PCD from the planning stage of a road through it's whole life cycle. Similarly in the US the potential benefits of SET are at all levels of the organizations planning, designing, constructing and maintaining the infrastructure and vehicle fleets. Communication among sectors is the most significant obstacle.

Maybe a better example for the higher level decision makers or managers is the popular Build-Operation-Transfer (BOT) model in financing and building the highway network. This model has been broadly adopted by the provincial and municipal governments in China, who are expected to provide about 80% of the total investment. Within this context, the advantages and necessities of applying SET are intuitively explored by a simple economic model.

If p is the average toll rate charged to the users of the road, v is the average forecast traffic volume per day, t is the operation period, f is the pavement permanence coefficient, then the current profit is given by the function π: $\pi = \pi\,(p, v, f, t)$. Under this simple rational, it seems that on one hand, the higher the toll rate, the more vehicles use this road, the more income could be collected; on the other hand, the better quality of the pavement, the longer t will be, and therefore, the more profit could be achieved. This could be shown as:

$$\partial\pi/\partial p > 0 \qquad \partial\pi/\partial v > 0 \qquad \partial\pi/\partial f > 0 \qquad \partial\pi/\partial t > 0$$
$$d\pi = \partial\pi/\partial p * dp + \partial\pi/\partial v * dv + \partial\pi/\partial f * df + \partial\pi/\partial t * dt > 0$$

However, none of these four variables can be isolated from the others. For example, if the performance of the pavement is decided by traffic volume and time, the function f could be written as f: $f = f\,(v, t)$. Again, the simple logic tells that the more vehicles using the road, and the longer the road has been used, the poorer performance is expected. Or using the following partial derivatives:

$$\partial f/\partial v < 0 \qquad \partial f/\partial t < 0$$

this gives:

$$\partial\pi/\partial v = \partial\pi/\partial v + (\partial\pi/\partial f)(\partial f/\partial v) \qquad \partial\pi/\partial t = \partial\pi/\partial t + (\partial\pi/\partial f)(\partial f/\partial t)$$

Because the signs of the two terms to the right of these two equations are opposite, an increase in the number of vehicles and the increase of time may or may not lead to an increased profit. This is only a simplified analysis. Actually, it is a problem of system dynamic optimization. For the investors, their concern is how to make the greatest profit π at the lowest cost before the point t in the future. After that, they no longer care about p, f and v. For the local government, the issue turns into how to impose regulations or inject incentives to maximize the sum of the profit π decided by p, f, v after that point t. For the government having BOT project(s) or planning to use the BOT model, developing a comprehensive model in the context SET would be helpful to achieve the sustainable system performance with lower cost.

Conclusions

The most difficult issues in applying SET to a real project are inadequate data, communication between disciplines and bringing to the project team persons with the necessary skills to represent each segment of the wheel. The main reason is that current data collection procedures are not designed to obtain information about the whole transportation system nor to disseminate that information to all interested users. For example, the data reflecting the interaction between the pavement and dynamic axle load distribution of vehicles has not been collected with standards and consistency. The data used were obtained from the experiments in the labs or pilot field projects. It was a time-consuming and expensive procedure, and more importantly, the data collected was only representative for certain vehicles and pavement types over a comparatively short period of time. Also current data collection should not be limited to certain kinds of vehicles, such as existing trucks and automobiles. There must be provisions for estimating future generation vehicles and their impacts. The impact of overweight vehicles must be appropriately included in the analysis as they cause a disproportionate part of the damage to pavement structures. The type of data, the level of detail and reliability, and the frequency and location at which they are collected, analyzed and updated need to be reconsidered and adjusted within the SET context.

Application of the SET principles is a valuable approach to analysis and design of highway projects. It is recommended for further implementation in real-world project in order to further develop the necessary tools to actually use it in a comprehensive manner to address real world problems.