Precision Without Accuracy: Heavy Trucks and Pavements Revisited

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1.0 Introduction:

Over the past ten years, the "art" of engineering pavements has become more and more of a science. Thanks to new developments in instrumentation, more precise ways of measuring pavement response to loads have been developed. New and sophisticated analytical and computing capabilities have made design and performance prediction easier. Research into pavement behaviour under loads has led to the identification of many new factors which have a potential effect on pavement life.

In spite of these steps forward in the science, the behaviour of many in-service pavements still does not meet with the expectations of the designers, owners or users of the public road system. The problems of deteriorating infrastructure in Canada and the U.S. have been widely cited elsewhere (1) (2), as has the need to invest additional funds in research to better understand and deal with the problem.

The research commitments have been made. The U.S. Strategic Highway Research Program (SHRP) and complementary national programs in Canada, Great Britain and the Nordic countries (among others) represent substantive coordinated programs of work aimed at addressing road infrastructure related problems. Similarly, over the last 5 years, a new recognition of the need to better understand the vehicle/road interaction mechanism has developed with consequent new research projects being launched in these areas as well.

Recent work in New Brunswick that began as an exploratory effort looking at the relationship between the occurrence of rutting and various characteristics of the pavement structure suggests that basic issues relating to the real nature of "as-built" pavements and the difference between "design" and "real" loading regimes have yet to be addressed in practice. These first-order issues are fundamental to the long-term performance of pavements but are largely ignored in the delivery, operation and management of road infrastructure.

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This paper begins by looking in a general manner at the problem of defining "useful" research and candidate regulatory measures for the truck size and weight domain in the context of pavement performance. The hazards of focusing on "precise" solutions to "fuzzy" questions are discussed. The final section of the paper is devoted to a review of the New Brunswick work as an illustration of the problem and its potential implications.

2.0 Problem Statement:

2.1 General Observations

With the continued growth in the importance of the motor transport industry in Canada (3) the motivation to continue the research carried out under the RTAC Vehicle Weights and Dimensions Study is still present. Nevertheless, scarce research resources have traditionally forced funding agencies to discriminate carefully among competing research programs and to be selective in their activities.

A close parallel exists within public and private agencies assigned the job of implementing research findings in regulation or technology. There, resources, historical agency policies and political priorities often mitigated against the implementation of measures that might have offered some degree of benefit.

In this context, potential regulatory (and consequently - research) priorities have been assessed against two basic criteria:

- Their possible impact
- Their "practicality"

The impact criteria differed depending on the particular issue being addressed. In the case of pavements, the criterion was usually some measure of "cumulative damage" or "pavement life". In the vehicle dynamics domain "safety" criteria were generally the appropriate measure.

Practicality was more difficult to define. To be practical, a regulatory measure had to have a reasonable expectation of being controllable or predictable and certainly, enforceable. The question of political and economic practicality had to be considered as well. At the research level, there had to be a realistic chance of successfully addressing the problem.

Although it represents an oversimplification, this evaluation concept is illustrated in matrix form in Figure 1. Here, parameters and relationships to be investigated are rated according to their relative impacts and their controllability. Desirable, first priority activities lie in the upper left corner of the matrix. A less rigid graphical illustration of this same concept is shown in Figure 2.

As research activities push the boundaries of knowledge further and further, they have begun to concentrate on parameters of interest in cells other than those containing first order variables. This is to be expected in a healthy research environment where new issues are continually being brought to light. Unfortunately, the real-life performance of pavements does not appear to have matched this progress. The state of knowledge at the research level now exceeds by a widening margin what is being "delivered" on the road.

The core of this problem is not erroneous research, but rather is a lack of recognition of the uncontrollability of certain first order variables. The application of very precise measurement and analytical techniques to "fuzzy" data will necessarily provide answers or predictions containing a wide degree of uncertainty - precision without accuracy.

2.2 Implications for Pavements

From the standpoint of truck size and weights, three primary elements directly affect long term pavement performance:

- The Road
- The Load
- The Vehicle

Within the road element, both the subgrade and the road structure are important components. From a vehicle standpoint, tires, suspensions and vehicle configurations must be considered. When looking at the loads, both magnitudes and frequency of application are important.

It is interesting exercise to assess each of these components in the context of pavement performance against three criteria - impact, controllability and predictability. The third rating dimension is intended to reflect the certainty with which input data is known. No attempt has been made to carry out such a rating, however three components are of particular interest in this work, road structure, load magnitudes and load frequency. Each of these variables represents a basic input into pavement performance prediction equations, yet up to now each has demonstrated a remarkable resistance to being accurately predicted or quantified.

Very precise methods exist for field measurement of strains and deflections in pavements (4) and highly complex analytical tools are also available for predicting such values. Techniques are also in place to apply the outputs of such work to the structural design of pavements. White (5) however points out the hazards of these approaches:

"... *deflection, strain, etc. will vary from point to point in the same pavement as well as between comparable pavements and conditions of test. The amount of variability of micro response type performance indicator data collected from real pavements may be a surprise to some pavement engineers and researchers that analyze ideal pavement sections with a mechanistic model and with assumed unique material properties.* "

Knowing the loading regime to which a road is being subjected is essential to effective pavement management and regulation of truck size and weights. The problem is not one of pavement load equivalency factors - a great deal of work has been done in this area, and while further research is still needed the level of understanding which has been reached in this specific subject area is impressive (6).

Pavement engineers can and do design pavements that stand up for the required number of load repetitions. In discussing an analysis carried out in Iowa on both asphaltic and portland cement concrete pavements, Cable (7) indicates:

"... *both materials are providing truck axle loading service equal to or greater than that called for in the original designs... the only difference noted was the rate of loading for each pavement. Several attained the design number of loads earlier in their life due to the unanticipated growth in truck traffic. They point out the need to improve the predictive techniques for truck number,* *size and weight for use in the design of pavements."*

Uncertainty with respect to the loading regime comes from two sources, the unknown frequency and magnitudes of truck overloads and the inability to accurately predict truck traffic into the future.

Figure 3 illustrates the problem caused by uncertainty in the input data to very precise analytical tools. Depending on the variable involved, input data can often be specified with a very high degree of certainty. Some data, however is probabilistic in nature. This includes information on the loading regime as well as data on the characteristics of the road structure. If the uncertain nature of the input data is not taken into account, then regardless of the precision of the analytical solution the real range of output values will exceed that which is "predicted" by the analysis. In other words, a very precise, but not accurate solution to the problem is obtained.

The case study that follows attempts to illustrate this problem and provides a discussion of its implications.

3.0 The Case Study:

3.1 General

In 1988 the New Brunswick Department of Transportation launched a study of wheel track rutting in New Brunswick. The mandate of the study was to examine the premature development of wheeltrack ruts on New Brunswick highways, with a particular focus on the pavement structure.

Twenty four sites were chosen throughout the province, covering a range of climatic, subsoil and traffic conditions. Rut depths were measured at each site in both inner and outer wheelpaths and nine core samples were also taken at each location. The rut depth measurements were taken to provide an assessment of the severity and extent of rutting in the province. The core samples were obtained to allow for an extensive program of laboratory testing and included locations outside, between and within the wheelpaths.

Standard laboratory tests were run on selected recovered cores. The program of testing focused on characterization of the mix design, asphalt properties and aggregate properties. Measures such as various densities, stability, AC content were used to define the mix design used. Asphalt penetration and viscosity were evaluated. Finally, aggregates were examined from the standpoint of both percentage of fractured faces and gradation.

3.2 The Rutting Study Summarized

The initial objective of the study was to explore any correlations between various characteristics of the pavement structure the occurrence of rutting. This objective was established after initial analysis of the core samples showed clearly that the rutting was associated with plastic deformation of the asphaltic pavement and not due to subgrade or sub-base deformation under load.

Based on the rut depth measurements and truck traffic estimates "rutting rates" were defined for each site and the sites themselves were categorized as "good" or "bad" based on a threshold rutting performance equivalent to the development of 20 mm ruts over ten years at a truck traffic level of 500 per day. A first-level analysis was carried out using data from core samples taken only in the wheel paths. It included a simple linear regression approach and a threshold analysis similar to that used by Saskatchewan in their rutting study (8). Both seal and base layers were examined.

The linear regression analysis was inconclusive and no statistically significant correlations could be found between rutting rates and the various road structure variables that were examined. The threshold analysis revealed little more other than the fact that values of variables including asphalt content, % air voids, VMA etc. found at sections that performed well in resisting rutting were consistent with good asphalt mix design. Unfortunately, similar values for many variables were also found at sections that performed poorly.

A second level analysis attempted to probe the data more deeply. In this case "in" wheel path and "out" of wheel path mix variables were examined to see if statistically significant differences existed between "good" and "bad" performing sections. These analyses focused on three variables: air voids, VMA and specific gravity (density). Once again, both seal and base layers were examined. Tables 1, 2 and 3 summarize the findings of this analysis for air voids, VMA and specific gravity respectively.

Average values of air voids were found to be consistent with normal practice for both good and bad sections. When each section was examined individually however, large variations in air voids were found across the nine cores. Only in one case was there found to be a statistically significant difference between good and bad sections. Air voids in the base layer of the wheel track of bad sections were found to be over 25% lower than the values found for good sections. A review of the analysis concluded that some degree of wheel track compaction was occurring, as opposed to lateral displacement of pavement.

The pattern of VMA values shown in table 2 was found to be consistent with the findings of the air voids analysis. No particularly alarming values were detected. Once again, the only statistically significant difference between good and bad sections occurred in the base layer of the wheel track, where VMA values of 14.2 % were found in bad sections versus a 15.2 % value in good sections. The pattern of VMA values confirms the conclusion of the air voids analysis that some degree of wheel track compaction is occurring.

The analysis of density summarized in table 3 was consistent with the pattern of wheel track compaction that appeared in both of the other analyses.

The investigations carried out in the course of the rutting study provided no strong evidence of consistent mix flaws which might help distinguish between road sections that were resistant to rutting versus those that were particularly susceptible. However, the degree of variation of certain mix properties across individual sites was particularly surprising and led to further investigation as to the nature of this variability.

3.3 Variability in Mix Properties

The analysis of pavement performance and the design of pavement structures is generally predicated on certain assumptions regarding unique material properties and the homogeneity of asphaltic concrete mix once it is placed. These assumptions are considered acceptable in practice, and the new AASHTO design procedure even makes some allowances for a probabilistic approach to design (9).

Notwithstanding this fact, the consistent degree of variability found in each of the 24 sites examined was surprising and gave rise to two fundamental questions:

- Is the source of this variability the construction process ?
- How does this variability affect pavement performance ?

Neither of these questions could be answered in the subsequent analysis. Because of space limitations only a summary is given here. It focuses on variations in air voids and stability although similar variations were found for other variables including aggregate gradations.

Table 4 presents the results of this variability analysis for six of the 24 sites in the study. Not all tests were available for all cores at all sites, however generally from 4 to 6 cores were evaluated at each location. When the range of data for each variable at each site is expressed as a percentage of the minimum variable value, the spread of values becomes evident.

For the six sites illustrated air void ranges were between 40% and 682% of minimum air void values. In the worst case illustrated, the mean air void value is 4.06 % and the standard deviation is 2.95. A review of that one site shows that the minimum value for air voids was 1.11 % and the maximum was 8.68. While occasional occurrences of this type could be attributed to lab error, all 24 sites showed variations of this sort on a consistent basis.

Values for Marshall stability showed similar but not as dramatic variations. Stability ranges between 49 % and 206 % can be seen in the table. In the worst case, the lowest value for stability was just over 1100 and the highest was over 3400. At this site, the mean stability was 2105 with a standard deviation of 1059.

The case for the existence of substantial spatial variation of properties within the pavement structure is definitive. The conclusions that can be drawn from the work are less so at this stage. Is the source of the variability at the asphalt production level or at the construction stage ? How localized are "weak" and "strong" areas within the overall pavement structure and how do such inherent weaknesses contribute to the deterioration or longevity of pavements ? Parameter variability is an accepted part of pavement design and performance prediction - but how much is acceptable and how can the degree of variability that is present be assessed ?

Work is continuing on this portion of the study in an attempt to provide some of the answers to these questions. Regardless of what is found however, there can be little doubt that what is "out there" and being used is substantially different from the theoretical, homogeneous structure with unique properties that pavement designers and analysts assume in their work.

3.4 The Loading Regime: Frequency

In considering the effects of truck weights on pavements over a "design life", both the number of load repetitions (rate of loading) and their magnitudes are important. The rate of loading was the first aspect of this problem that was explored. Previous work by Gould (10) using data from a 1984 truck origin/destination study carried out in New Brunswick pointed to problems with the accuracy of truck load data. The intent of this analysis was not to provide a definitive link between loading rates and rutting as insufficient data was available to accomplish this. A more speculative approach was taken and aimed at providing some idea of how realistic the original design truck traffic projections and their consequent ESAL loading rates were in the context of today's traffic levels.

To carry out this work, data was taken on a 100% sample basis at the Long's Creek weigh station for 8 hours between 8 a.m. and 4 p.m. This scale is located on the Trans-Canada highway - the major interprovincial truck route in the province of New Brunswick. Data collected included single axle and axle group weights, axle spacings and vehicle configurations. Straight trucks were included in the sample.

Load equivalency factors were calculated for each axle and axle group on every truck and summed to give a truck equivalency factor for each vehicle passing through the scale. Data from the RTAC Weights and Dimensions study (11) were used to calculate the load equivalency factors. Subsequently, average truck equivalency factors were calculated for each truck type from 2 axle straight trucks through 6 axle vehicles. The results of this analysis are presented in Table 5.

These truck factors were then used to estimate the loading accumulation that would occur on the Trans Canada Highway over a 20 year period assuming a 2.5 % annual truck traffic increase, with no change in fleet make-up and allowable size and weight regulations during that time. Even at present day traffic levels, the highway accumulates over half a million ESAL's per year. When growth is factored in, it is expected that over a 20 year period the highway would be subject to over 15 million ESAL's. This is far in excess of what is normally expected over the "design life" of a highway of the type in question.

While the procedure presented above is simplistic and certainly subject to criticism from a statistical standpoint - it is acceptable as a sensitivity analysis and is sufficiently accurate to be indicative of the order of magnitude of the problem at hand. In fact, the results have to be considered somewhat conservative when it is realized that no overloaded vehicles were included in the truck sample used as a basis to calculate the truck load equivalency factors.

The point to be drawn from this analysis is simply that design load rates do not bear any relation to the actual rate of loading of in-service facilities. " Early " rutting or highway deterioration may in fact be a perfectly normal result of using up the highway's design ESAL's.

3.5 The Loading Regime: Magnitudes

Because of its illegal nature, the magnitude of vehicle overloads actually occurring on the highway system is difficult to assess accurately. The impact of an overloaded vehicle in terms of additional damage to the road structure however has been well documented - most recently in the Canadian context by the RTAC Vehicle Weights and Dimensions Study (12). Once again, a speculative approach was taken to assessing the order of magnitude of at least one of the most obvious forms of overloading that is known to occur - that of fully loaded six axle tractor semi trailers running with the belly axle in the lifted position.

The same data from the Long's Creek scale was used for this work. Of the 283 trucks passing through the scale in the eight hour day, 34 % were 6 axle tractor semi-trailers equipped with air-lift axles on the trailer. Of these, two thirds were running loaded with an average 26 500 kg on the three axles of the semi-trailer.

RTAC data indicated that the Load Equivalency Factor for an axle group consisting of a tandem plus belly axle at 26 000 kg. was in the order of 2.6. Thus, if all of the 66 loaded vehicles ran as required, their accumulated ESAL impact would be in the order of 172 ESALs for the three trailer axles.

If on the other hand, even half of the vehicles ran loaded with the belly axle raised - a not uncommon practice - the cumulative wear due to the triple axle group would increase to almost 280 ESALs. This represents an increase of over 60 % in cumulative wear over the comparable group of legal vehicles. If the percentage running "belly-up" while loaded is increased to 75 %, the cumulative damage due to the same 66 vehicles increases to over 330 ESAL's. This represents a 93 % increase in damage over the base case.

Over the course of a year, given the truck traffic volumes and fleet make-up on the section of the Trans-Canada from which data was taken such a hypothetical 75 % "belly-up" case would mean that the cumulative ESALs due to the triple axle groups of such trucks would be in the order of 212600 instead of the 110000 which would occur under fully legal conditions.

While speculative, this scenario is probably not unrealistic in terms of what is happening on the highway system. The real magnitude of the overload problem goes much farther than just the belly axle case illustrated above. The problem isn't so much that overloads exist as the fact that there is no exact information as to what the size of the problem really is. Without knowledge of the real loading spectrum to which the road infrastructure is being subjected effective design, operation, maintenance and management of the system is impossible.

4.0 Conclusions:

The purpose of truck size and weight regulation is to allow for the effective management of highway infrastructure. Researchers have made substantial strides in the past decades in increasing the tools available for this purpose by improving our understanding of the factors at play. While the degree of sophistication of current research efforts is both admirable and desirable, a number of fundamental issues remain to be addressed.

The case study described above has attempted to illustrate this problem. No alarming failures or dramatic shortcomings were found in the course of the rutting study. However, new avenues of investigation were opened to address questions related to the nature, magnitudes and effects of pavement structure variability on long term performance. The role of construction processes in contributing to that variability have also to be explored.

While speculative in nature, the review of load related questions has raised serious concerns as to the validity of data currently used for design and performance prediction. This phenomenon is not unique to New Brunswick. Indications are that real-world loading regimes are substantially different in terms of both frequency and magnitude than those used for design and forecasting purposes. Many jurisdictions, including New Brunswick have, or are in the process of developing systems to allow for much more accurate collection of this data. Without such efforts the use of erroneous or fuzzy input for this very basic data will continue to confound the efforts of highway system operators to grapple successfully with truck size and weight impacts on highway pavements.

The issue raised by the continuing growth of the trucking industry and the related decline of the railways has to be addressed in both truck traffic forecasting procedures and related pavement design methodologies. Research currently underway at RTAC indicates that this trend is expected to continue through the turn of the century. This fact has to be recognized now, since infrastructure that is being built, rebuilt or rehabilitated will have to serve under increasingly severe loading regimes.

Finally, the evaluation of new research directions and proposed regulatory measures must necessarily focus on efforts that offer practical solutions which have substantive impacts that can be realistically implemented. Strategy without execution has no value.

5.0 Acknowledgement

The assistance of the New Brunswick Department of Transportation (NBDOT) in this work through the provision of data is gratefully acknowledged.

Of course the contents of this paper and the viewpoints expressed therein are exclusively the responsibility of the authors and do not necessarily reflect the official views or policies of NBDOT.

6.0 References:

1: **Roadway Infrastructure Study: Update Report**, Roads and Transportation Association of Canada, Ottawa, 1988.

2: **Our Nations's Highways: Selected Facts and Figures.** Office of Highway Information Management. Federal Highway Administration, Washington, D.C. 1987.

3: **Trucking in Canada: 1986.** Statistics Canada, Ottawa, 1988.

4: **Full Scale Pavement Tests.** Organisation for Economic Cooperation and Development, Paris, France. 1985.

5: White, T., **Overview of Pavement Response.** Paper given at FHWA Load Equivalency Workshop, Sept. 13 - 15, 1988. McLean, Virginia.

6: Rauhut, B., **Overview of Load Equivalency Factors.** Paper given at FHWA Load Equivalency Workshop, Sept. 13 -15, 1988. McLean, Virginia.

7: Cable, J.K., **Pavement Loading/Design Relationships in Iowa,** Proceedings of the International Symposium on Heavy Vehicle Weights and Dimensions, June 8 - 13, 1986. Kelowna, B.C.

8: Huber, G.A., Heiman, G.H., **Effects of Asphalt Concrete Parameters on Rutting Performance: A Field Investigation.** Paper presented at 1986 RTAC Annual Conference. Toronto, 1986.

9: **AASHTO Guide for Design of Pavement Structures: Vol.2**, Appendix EE: Reliability Elements and Variance Estimates. AASHTO, Washington, D.C. 1986.

10: Gould, D., **The Cost of Pavement Damage on New Brunswick Provincial Highways** . Unpublished report, University of New Brunswick. Fredericton, N.B. 1988.

11: Christison, J.T., **Pavement Response to Heavy Vehicles Test Program: Part 2 - Load Equivalency Factors**. Canroad Transportation Research Corporation. Ottawa,1986.

12: **Vehicle Weights and Dimensions Study**: Technical Steering Committee Report", Canroad Transportation Research Corporation. Ottawa, 1986.

TABLE 1

AIR VOIDS ANALYSIS

	SEAL LAYER	BASE LAYER
In Wheel Track	3.6% (G)	4.6% (G)
	3.1% (B)	3.4% (B) *
Out of Wheel Track	5.8% (G)	4.8% (G)
	5.5% (B)	4.4% (B)

(G) Indicates "Good" Section
(B) Indicates "Bad" Section
* Statistically Significant

TABLE 2

VMA ANALYSIS

	SEAL LAYER	BASE LAYER
In Wheel Track	16.8% (G)	15.2% (G)
	16.9% (B)	14.2% (B) *
Out of Wheel Track	19.1% (G)	15.7% (G)
	18.8% (B)	15.2% (B)

(G) Indicates "Good" Section
(B) Indicates "Bad" Section
* Statistically Significant

TABLE 3

SPECIFIC GRAVITY ANALYSIS

	SEAL LAYER	BASE LAYER
In Wheel Track	2.331 (G) 2.347 (B)	2.351 (G) 2.388 (B)
Out of Wheel Track	2.279 (G) 2.294 (B)	2.338 (G) 2.363 (B) *

(G) Indicates "Good" Section
(B) Indicates "Bad" Section
* Marginally Statistically Significant

TABLE 4

VARIABILITY ANALYSIS

SITE	PARAMETER	MEAN	STANDARD DEVIATION	MAX. VALUE	MIN. VALUE	RANGE	%
A	Air Voids	2.75	0.476	3.29	2.35	0.94	40
	Stability	4736	685	5519	3710	1809	49
B	Air Voids	2.924	1.371	4.99	1.53	3.46	226
	Stability	4325	641.7	5035	3240	1795	55
C	Air Voids	5.426	3.312	9.73	1.78	7.95	447
	Stability	6010	1118	7911	4933	2978	60
D	Air Voids	4.684	2.931	9.66	2.09	7.57	362
	Stability	3336	1078	4442	1485	2957	199
E	Air Voids	5.344	2.013	7.5	3.13	4.37	140
	Stability	2702	553.9	3177	1979	1198	61
F	Air Voids	4.06	2.949	8.68	1.11	7.57	682
	Stability	2105	1059	3403	1113	2290	206

TABLE 5

TRUCK LOAD EQUIVALENCY FACTORS

TRUCK TYPE	AVERAGE EQUIVALENCY FACTOR
2 axle	1.089
3 axle	1.314
4 axle	1.514
5 axle	2.677
6 axle	4.557

FIGURE 1

WHERE SHOULD WE WORK ?

IMPACT →

CONTROLLABILITY ↓

	HIGH	MEDIUM	LOW
HIGH			
MEDIUM			
LOW			

FIGURE 2

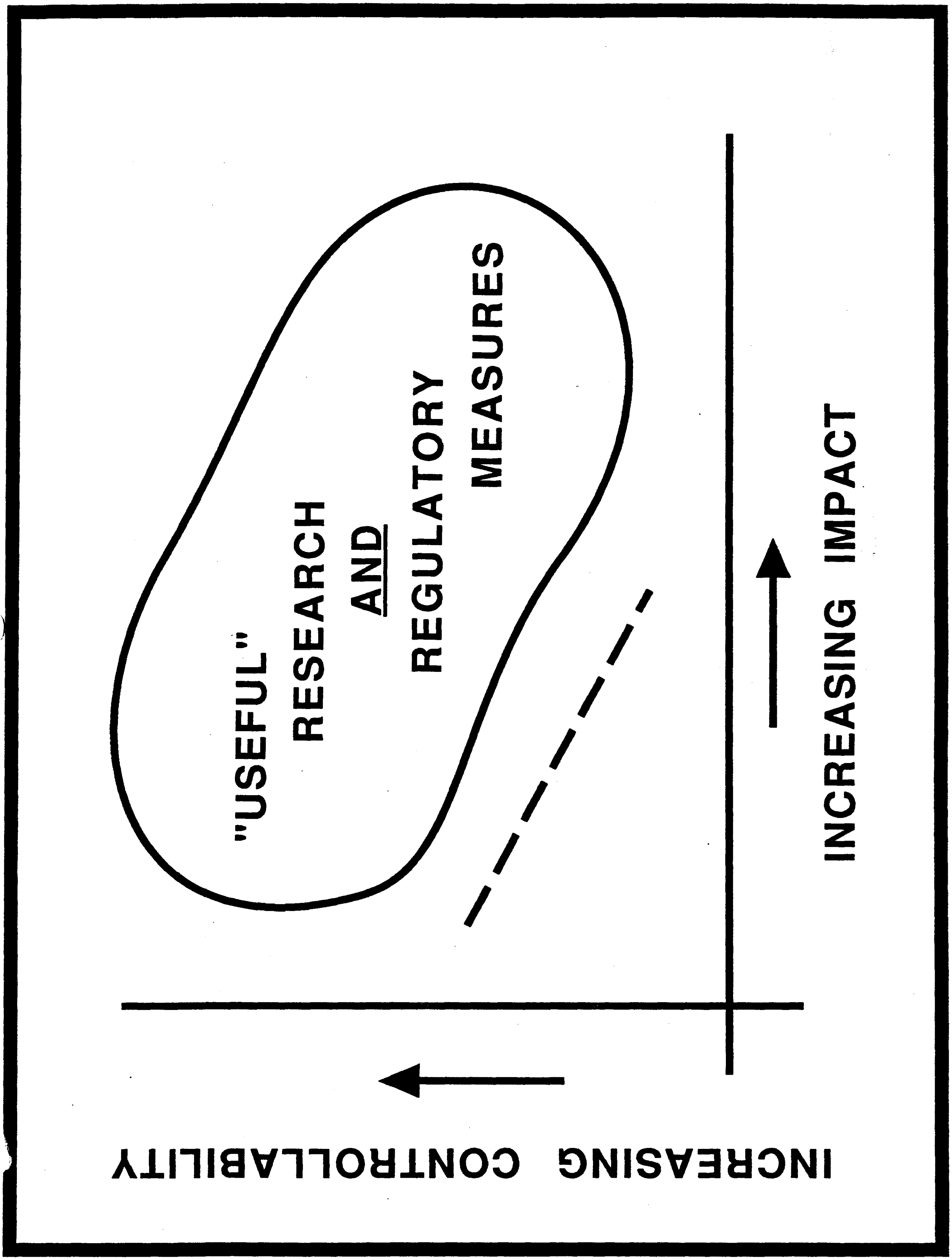
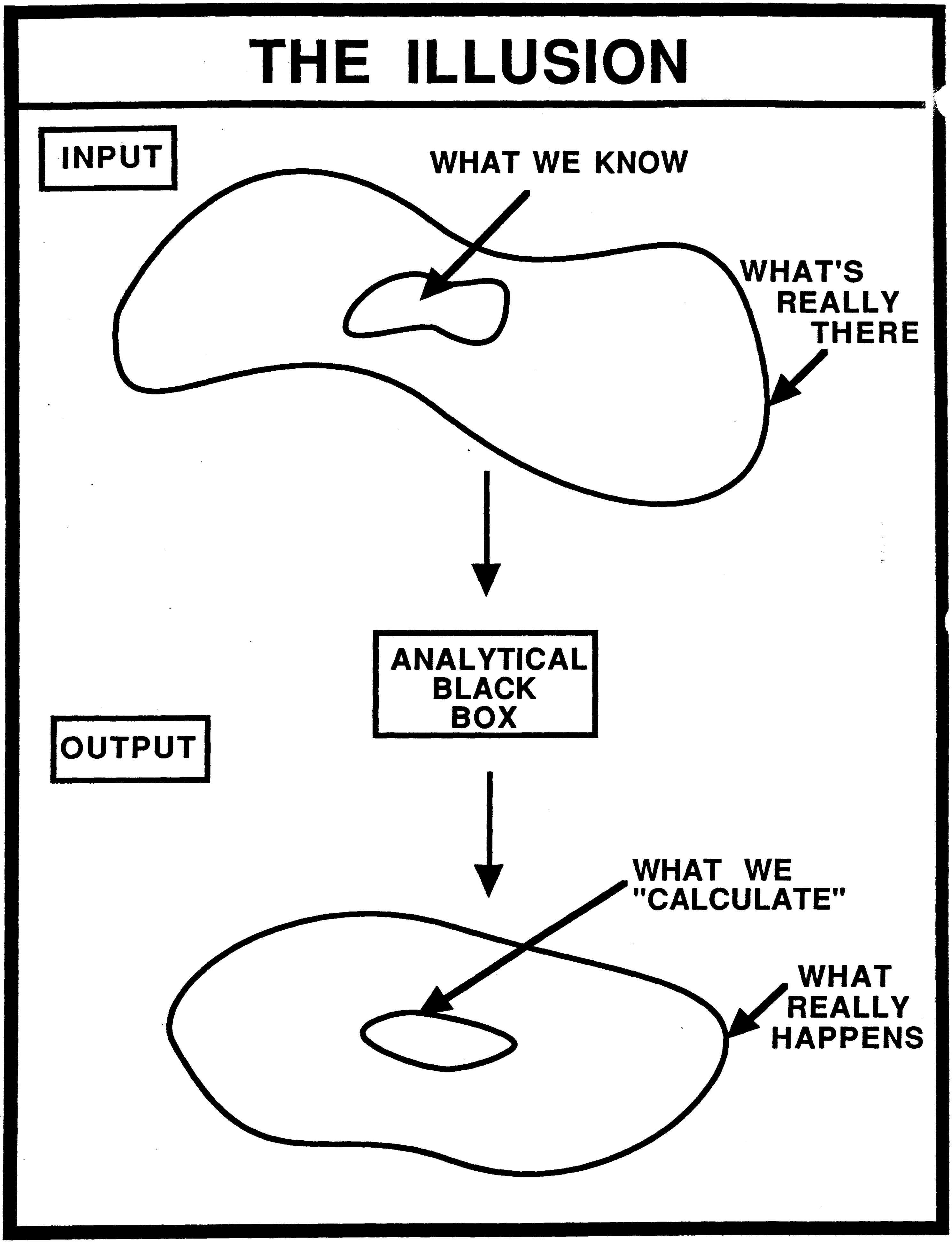

"USEFUL" RESEARCH AND REGULATORY MEASURES
INCREASING IMPACT
INCREASING CONTROLLABILITY

FIGURE 3


THE ILLUSION