

IMPACTS AND BENEFITS OF APT: AN APT OPERATOR'S PERSPECTIVE

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ABSTRACT

The primary purpose of this paper is to provide a summary of the impacts and benefits of accelerated pavement testing (APT) from the point of view of an APT operator, based on personal observation of the California APT program and other programs. APT was not the only factor in obtaining the benefits of pavement research and this paper also seeks to define the unique roles that APT played in obtaining those benefits, and identify those roles in the work summarized. The paper also discusses the benefits obtained from collaboration between APT and other investigatory techniques, and between APT programs. Finally, this paper identifies limitations of APT that, in the authors' opinion, can be addressed by collaboration between the two primary types of APT, fixed devices and test tracks, and with construction and long-term monitoring of field test sections.

INTRODUCTION

APT programs are expensive to operate, and must lead to implementable results that produce benefits for the sponsoring organization in order to continue. Some of those benefits are obtained many years after the original work was performed, by combining results from different experiments, thus increasing the benefits from the original work. The hope is that this paper will provide ideas to other programs (and reflection for our own program) as to maximizing the benefits from APT, and demonstrating the return on the investment made in these APT programs. This paper also presents ideas for further increasing the benefits of APT based on the California experience by combining what the HVS can do best with what other types of testing do best. These are not necessarily new ideas, as evidenced by historical use of APT, but are worth reiterating, reviewing and refining and where useful, formalizing into the APT program.

For nearly as long as engineers have been providing formal pavement design guidance in this era of rubber-tired vehicles, they have identified the need for Accelerated Pavement Testing (APT). Early pavement design methods relied on observation of the performance of in-service pavements, correlated with relatively simple laboratory tests of the bearing resistance of pavement materials and the relative loads and numbers of load repetitions placed on the pavement by traffic. An example is the California design method developed in the 1920s by O. J. Porter based on the California Bearing Ratio (CBR) test correlated with observed truck traffic and performance, and subsequent development of the empirical California design methods under the direction of Francis Hveem and his successors.

However, the monitoring of in-service pavements to produce timely improvements to empirical pavement design methods and improvements in materials specifications (type, design and construction quality) was severely limited by:

- the amount of time it took to build in-service pavement sections and obtain performance measurements,
- the high risk of experimenting with in-service facilities,
- the difficulty of measuring and retaining traffic, climate and performance data over the service life in order to extract the answers at the end of the study many years later,
- the difficulty of building on in-service facilities the pavement test sections needed to complete an experimental design while controlling for those variables not included in the experiment.

Because of these issues Accelerated Pavement Testing (APT) has been recognized as necessary, and has been used, to advance pavement technology since the time of the early modern pavement design methods, in numerous locations. As an example, one arc of this type of development that relied on APT was used to develop design methods in California, including:

- the Stockton Test Section (1942) shown in Figure 1, where a loaded wheel was dragged up and down a pavement with varying thickness of granular base and a thin asphalt layer at an airfield, results of which were used by the (then named) California Division of Highways and the US Army Corps of Engineers to develop basic relations for the amount of granular base required to protect the subgrade for highway and air field pavements, respectively (1);
- the Brighton Test Track (1940-1943);
- the WASHO Road Test (1951- 1953) near Malad, Idaho which compared several flexible pavement designs out of which came the concepts of Equivalent Wheel Load

- Factors (EWLF) which later became Equivalent Single Axle Loads (ESAL), and deflection testing using the Benkelman Beam;
- the AASHO Road Test (1958-1960) at Ottawa, Illinois, which was used to compare pavement types (concrete and asphalt), to measure the effects of axle types and loads on performance, and to define performance in terms of ride quality. This data was used to re-calibrate the California design method based on the R-value test for soil shear resistance.
 - Limited comparison of in-service performance with design practice (2).

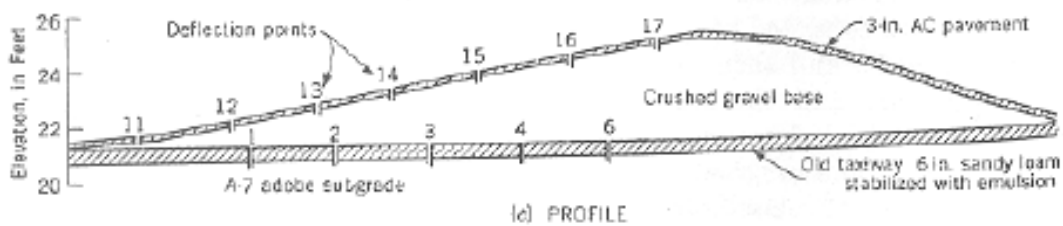


FIG. 13.—STOCKTON RUNWAY TEST SECTION

FIGURE 1 Cross section of Stockton Runway Test Section (1942) used for APT testing (1).

It is interesting to note that this example arc of development for California empirical design methods included the use of fixed devices (Stockton Test), closed-circuit test tracks with full-scale vehicles (Brighton, WASHO and AASHO Road Tests), organization of the resultant practice around laboratory testing of materials used in the APT test sections and in-service pavements, and attempts at comparison of the APT results with in-service performance. Much, but not all, of the work performed was implemented into standard practice over time, capturing the benefits of the research and development work. California was also an early leader in establishing a first-generation pavement management system (PMS). The PMS should be the feedback loop connecting research with practice through monitoring of the entire network to a lower level of detail, and monitoring of selected sections at a level necessary to validate and re-calibrate models developed from research through Long-Term Pavement Performance (LTPP) monitoring.

Figure 2 shows the progression of laboratory testing (no computers at the time!), APT and long-term monitoring that was used by the then California Division of Highways to develop its design method for flexible pavement.

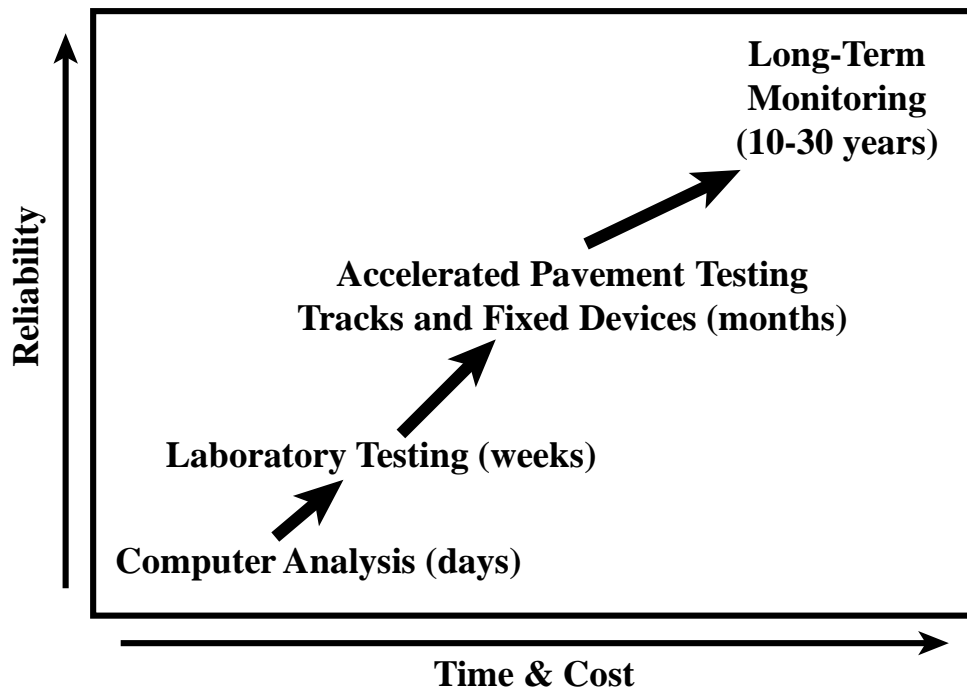


FIGURE 2 Relationship between tools used to develop pavement technology.

The need to obtain an ongoing APT capability to again increase the pace of pavement technology development and to develop more mechanistic approaches to pavement technology led the California Department of Transportation (Caltrans) to purchase two refurbished Heavy Vehicle Simulators (HVS) from South Africa in 1994. Since then, Caltrans has also established an expanded pavement research capability in partnership with the University of California, Dynatest Consulting Inc and CSIR (South Africa), also to increase the pace of pavement technology development. All of the APT work performed in California has been performed in a framework of improved understanding of the mechanics of pavements, with empirical calibration.

Costs of APT

A fact about APT that cannot be denied or hidden is that it is relatively expensive. The costs vary from program to program, depending on local costs and the unique organizational and cost-sharing aspects of each program. However, the cost items shown in Table 1 are necessary to operate an HVS based APT program regardless of how they are paid for.

TABLE 1 Cost items for HVS based APT programs

Cost Item	Comment
<i>Operating Costs</i>	
APT device initial cost	One-Time
Site costs	Traffic control (field), access, security, shelter for staff and equipment, communications, etc
Test section construction	
APT operating energy	Diesel or electric shore power, proportional to load repetitions
APT device maintenance	Proportional to load repetitions
APT device operating and data acquisition labor	More efficient if continuously operated, high level of training
Instrumentation	
Project Engineer(s), test management, quality control, data management	Continuous
Research Engineer, first-level analysis of APT data and first-level report writing	
<i>Additional Costs to Obtain Benefits of APT</i>	
Materials sampling at construction	Can include at plant as well as site
Forensic investigation and materials sampling	Necessary to determine failure mechanisms, effects of variables affecting results not in experiment, quantification of some distresses (examples: rutting in different layers, final concrete strengths)
Laboratory testing on construction and forensic samples	Necessary to interpret the APT results, particularly with regard to as-built as opposed to designed variable levels
Research Engineer(s), first-level analysis of laboratory data and first-level report writing	
Database manager, access, hardware	
Administrative support	

The cost items identified in the table above are for obtaining and analyzing the first-level analysis results from direct comparison of the variables included in the APT experiment. They do not include additional testing for site selection and identification of comparable locations for test sections, such as coring, trenching, condition survey and deflection testing. Nor do they include additional laboratory testing to extrapolate the APT results, such as preparation and testing of test section materials specimens with different mix proportions or source materials (aggregate source for example), construction quality, under different temperatures and stress/strain conditions, with different age and moisture conditioning, and with different compaction. They also do not include the costs of additional modeling, or other analysis to understand, interpolate and/or extrapolate from the variables in the APT experiment design.

One major cost that is shown in the table is the cost of maintaining, updating and operating a relational database for all data produced by the APT program (see the paper by Lea at this conference). These include:

- construction quality data,
- materials testing data from before, during and after APT testing,
- load, climate and response instruments and other measurements during the APT loading,
- related pavement testing data such as Falling Weight Deflectometer (FWD) deflections before, during (if possible) and after APT testing
- forensic data collected from cores, trenches and other destructive measurements after APT testing.

The author would argue that all of these costs must be incurred to capture the full benefits of APT. In addition to these costs, there is an opportunity cost that is lost by investment of public funds in APT with resources that could have been invested in some other type of pavement research, directly into road maintenance, or something else that would provide social benefit.

IMPACTS AND BENEFITS OF APT

Producing the Impacts

The purpose of APT is to provide a more cost-efficient answer to questions. The direct impacts of APT come from its ability to answer certain types of questions. The benefits come from implementation of the answers to the questions into pavement practice. The major types of questions that can be answered in a most cost-effective way with APT can be summarized into the following areas:

1. Identification and highlighting of deficiencies in current practices, typically related to weak or non-existent construction standards that if changed will increase the life of maintenance and rehabilitation projects, and/or avoid the risk of early failures;
2. Evaluation of materials, designs, materials specifications or construction standards before full scale implementation;
3. Comparison between alternatives for materials, designs, materials specifications or construction standards under controlled conditions to determine the most cost-effective solutions to problems.
4. Assessment of the impact of changes in vehicle technology (tires, wheel or axle types, suspensions, loads) on pavement performance.
5. Development of insight regarding pavement mechanics and damage mechanisms and validation and calibration of models for pavement analysis and design, including the following two elements:
 - a. Mechanistic models of the response of the pavement to water, temperature and load in terms of deformations, stresses and strains, and changes in the materials acting in the pavement system under these conditions.
 - b. The preliminary empirical calibration of damage models, prior to moving to field calibration.

The original focus of APT, and the initial projects of most APT operators when starting their programs, has been on direct empirical comparison of different structural and material designs, different materials and construction practice and quality on performance. This typically

involved execution of an APT testing plan consisting of a factorial of the variables of interest, including control sections for quantitative comparison of current alternatives with the new alternatives and qualitative extrapolation of those results to field performance. If the new alternatives perform better, and can also be improved through some iterations, then the new technology is moved into practice and benefits are accrued from the improvement in performance and associated reduction in life cycle cost.

These types of studies can be extremely effective. An example of each of the first four types of study listed above from the California program includes:

- HVS results confirming laboratory findings of improvements in fatigue life from requiring better compaction of dense-graded asphalt mixes, and use of tack coats.
- HVS results showing at least equal performance for reflection cracking of half-thickness overlays with mixes containing recycled tire rubber compared to full-thickness overlays with conventional hot mix asphalt (HMA).
- HVS results comparing the performance of jointed plain concrete pavements with asphalt shoulders, tied concrete shoulders and widened truck lanes.
- Assessment of the impact of the historical change from bias-ply tires to radial tires, and the potential change to wide-base single tires, with increasing tire pressure with each change.

The fifth type of study, the validation and calibration of pavement analysis models, usually requires the accumulation of the results of a number of experiments of the first four kinds. The key to the success of this kind of study is the inclusion in the experiment designs of the first four types of study the collection of mechanistic response data, high levels of quality control and assurance on that data before it is put into the program database, and retention in a relational database.

A further benefit of the fifth type of study is that once the models are reasonably well validated and calibrated the models can be used with laboratory test results to test additional materials and structures similar to those of the APT experiments at much lower cost than performing APT on a multitude of additional sections. The models can also be used to “re-run” the APT test sections through simulation with completely equal underlying conditions, temperature, water content, etc. Because there are inevitable differences in conditions that are supposed to be equal between APT sections, this simulation of the APT tests is extremely useful to confirm that the results of the initial empirical comparisons of performance do not change significantly under absolutely uniform conditions. While these two benefits can, to some extent, be realized from a single study and some advanced modeling, it is only when multiple studies are combined that there is really the breath of data to support these extrapolations.

Capturing the Benefits

Direct Benefits

The benefits from answering questions with APT studies come from implementation of the answers, which in business terms is often referred to as “market penetration.” The maximization of the benefits from APT comes from consideration of a research and development process that can be outlined as follows:

- Identification and selection of problems that present the possibility for the largest benefits. For many problems this can be done in a semi-quantitative manner by estimating the product of the
 - Estimated percent change in cost of answering the question,
 - Estimated percent of the agency’s operations costs affected by answering the question, and
 - Estimated percent of the potentially affected operations that will actually change as a result of answering the question (actual penetration of the potential market), knowing that in many cases answering the question will not be enough to result in a change of practice.
- Multi-level documentation, reporting and development of the results working with the client, including:
 - Full documentation in research reports that will allow the results to be fully understood, and especially to permit “mining” of the results years afterward to answer new questions (hundreds of pages). The audience is technical reviewers and other researchers.
 - Summaries of the experiments, results and recommendations for implementation (tens of pages). The audience is technical managers.
 - Technical marketing summaries of the experiments, with much less technical language, graphics of results, and recommendations for implementation (several pages). The audience is higher-level executives with some technical expertise.
 - Marketing summaries, stating the question answered and the non-technical reasons why it was important, the conclusions and the recommendations for implementation (one page). The audience is non-technical government and industry executives, and the public.
 - Working with the research client (technical managers and staff, after being given direction by executives) to convert the research results into policy by inclusion in the working documents used by practicing engineers and planners. These include specifications, design methods, standard plans, design and analysis software, design catalogs, design policy directives, standard project scoping processes, etc. The audience is the practicing engineer and planner.
- Presentation of research results in a timely manner to research peers at conferences and in journals. This is important to make the conclusions drawn from the results more robust, and to provide fresh thinking regarding the results. In addition, if the results are good, the comments of outside experts who are completely independent of the APT organization and the client’s organization can carry a great deal of weight with decision-makers in the client organization regarding implementation of results and the quality of the research. California participates in a peer group of the state departments of transportation from Minnesota, Texas and Washington State and their

associated research universities that provide an additional forum for this type of review.

None of these ideas is particularly new to the world of APT, and the benefit assessment process has been greatly clarified by the thinking discussed in another paper in this conference by du Plessis et al. Many of these steps do not need to be as formal as is outlined here in smaller organizations and pavement industries. The experience is that when the implementation process for APT results involves large and complex interactions and widespread communication, more formal adherence to a process of this sort is more important.

Additional Benefits

There are additional benefits from APT, many of which have been discussed previously (3), including:

- Providing a focus for pavement research that leads to a more efficient technology development process,
- The ability to closely observe and document construction practice and understand its effect on performance,
- Ability to develop, validate and calibrate mechanistic performance models that permits wider use of the APT results,
- The ability to do full-scale monitoring from construction through trafficking to failure, and document the results in a short enough period of time that the same team is involved from start to finish.

Each of these additional benefits requires some extra effort and costs on the part of the APT organization and its clients, but can significantly increase the benefits.

It has been clear from every APT program that the author has observed, that an APT program brings high-level attention to pavement problems. This is in part due to its cost! But APT produces results that can be viscerally understood by decision-makers who are not pavement researchers, in a manner that cannot be remotely equaled by researchers presenting results of a computer simulation or laboratory test, or a network-wide set of field test sections. APT also physically focuses research in one large-scale facility that usually brings together the researchers, the computer simulations, the laboratory testing, the APT sections, and the equipment used to test field sections. All of these have extremely powerful, yet difficult to document effects on the attention given by non-technical decision-makers as well as pavement technologists to the questions being addressed by the research.

One other benefit of this focusing of attention is that an APT program that considers the entire process of pavement technology development shown in Figure 2 will bring together mechanistic modelers, experimental researchers, and empirical network-level modelers, each of whom can tend to develop a warped sense of perspective on the importance of different questions and approaches to solving problems when they work in isolation. This can often result in what has been described (attributed to Thomas Huxley) as the “brutal slaying of elegant theories by cold, hard facts.”

Related to this is the opportunity that a large APT program provides for training and education. Because the program is well funded and operates over a number of years, it provides an ideal environment and suitable thesis material for doctoral level study, as well as providing an environment where laboratory staff, operators and others can learn a variety of skills in an environment which is geared towards a thorough understanding of pavement behavior, and the

tools to achieve that. It is interesting to look at the author list on some of the early HVS reports from South Africa and compare that to current list of partners in large pavement consulting firms. While a smaller program might be able to provide an excellent grounding on a single aspect of pavements, the staff and students produced by APT programs tend to have a broader range of skills. The benefit of this is that they are able to take this training and apply it to a wide variety of projects, in addition to implementing the insights gained through the specific APT studies they were involved with. There is an opportunity here for APT owners to use the programs to 'fast-track' employees through internships and staff exchanges, along with the formal degree based education of students.

An advantage of APT is that the same team associated with a project over a period of several months to several years typically stays with the project from the planning stage, where the questions are posed, through experiment design, construction, trafficking, analysis and documentation. This is not generally true of LTPP, which can take decades, and in which the people observing the failures and documenting the performance are almost never the same people who posed the questions and designed the experiment.

Another type of very important indirect benefit of an APT program is that it brings together pavement constructors with pavement researchers. Many of the benefits that have occurred from the California program have come from close observation of construction practices and measurement of the effects of construction which were not originally included in the experiment by researchers with a background in materials and pavement modeling. Additional benefits come from the personal interaction of the contractors with the researchers during construction of the APT sections, which has often resulted in insights that greatly aid implementation of the research results. A greater appreciation of the larger impact of construction on pavement performance as opposed to design is the usual result of this type of interaction, which will only increase the benefits from the APT program, including the selection of research questions to answer.

Quantification of Impacts and Benefits

Most APT operating organizations have not had to systematically quantify and document the benefits of their program on an ongoing basis. Usually this is only done on a periodic ad-hoc basis when there is a potential cut in the budget or shutdown of the program. However, in a world with evermore constrained and expensive resources and increasing demands on their transportation systems, answering the question of the financial efficacy of an APT program almost becomes an ethical concern. Particularly as programs mature, the continued efficiency of the program in providing cost-effective answers to questions must be routinely addressed. Performance measures for pavement research organizations should be financially based, just as they should be for pavement operating organizations, particularly where public money is involved that could go to other social uses or returned to taxpayers.

When compared to research and development in other industries, it is sometimes difficult to quantify the benefits of pavement research, and accelerated pavement testing in particular. Some of the reasons for the difficulty of quantifying benefits are discussed in more detail in the paper at this conference by du Plessis et al. Mostly they involve the difficulty of tracing the direct link between understanding of the results by implementers and the actual implementation, since there can often be a number of years between completion of the research and full implementation (market penetration) of the results. APT often results in multiple and poorly documented changes in the decision-making and operations within a pavement owning

organization, which are much more difficult to measure than how many iPods have been sold, or how many people are using a new pharmaceutical. It has been informally observed by a number of pavement researchers that the average time between identification of the question to be answered and full implementation of the results of the research is 10 years, and that there typically many more years before the benefits of implementation can be measured. By the time the benefits are to be measured, there are usually few people who remember what the original question was that led to the research, and the changes caused by the research implementation have become part of standard operating procedures.

A very good approach for preliminary measurement of the benefits of APT is presented in the paper by du Plessis et al at this conference and this approach is currently being tested in California. It can be argued that this type of approach should be applied to the selection of questions to be answered by APT as part of a strategic planning process, as well as applied to the actual implementation. The final and best long-term measurement of direct APT benefits will come from better connection of pavement research with pavement management systems, including more comprehensive linking of project-level construction materials and quality data with pavement performance data in pavement management systems.

SOME IDEAS FOR INCREASING THE BENEFITS OF APT

The direct benefit to cost ratios that have been calculated for a few of the APT projects completed by the California program are in the range of 3.2 to 9.5 (4). An early calculation for the South African program showed a benefit cost ratio of 12.8 (3). Additional assessments and calculations for elements the South African program have also been made several times (5, 6).

The following are some ideas for increasing the benefits that come from APT programs. There is no claim that these are new ideas, rather these are common-sense ideas, many of which have been discussed elsewhere that have been clearer to us as APT operators after 13 years of operation. These ideas are:

- The need for ever greater connection between all of the types of pavement research tools shown in Figure 2, and the need to relate information between them. This also includes building relationships between pavement researchers who focus on each of the types of tools shown in the figure.
- The relationship between the five types of studies (short-term and long-term) discussed previously, and their connection through the continuous maintenance of relational databases capturing and relating all of the different types of data collected, which permit researchers to return to previous experiments and mine useful data.
- The need for partnerships between fixed APT facilities, such as the HVSs operated in California, and closed-circular test tracks

A major effort is underway in California regarding calibration of mechanistic-empirical design and analysis models, similar to the effort made more than 50 to 75 years ago described at the beginning of this paper. To develop and then validate and calibrate those models for flexible pavements requires:

- Comparison of field measured properties of materials in pavement structures with laboratory measured properties. Laboratory properties will be used for design, and are intended to identify properties as they will occur in the field structure.

- Comparison of the calculated pavement response, in terms of stress, strain, deflection, to traffic loads and environmental changes, ie temperatures and state of moisture, with actual response in the pavement structure.
- Comparison of the damage to the pavement layers, in terms of loss of stiffness and permanent deformation, between the calculated values and the pavement in the field.
- Comparison of the calculated variability of all of the above due to the intrinsically stochastic nature of underlying conditions, pavement materials, pavement construction, traffic loading and climate with actual variability.

APT and its associated laboratory testing, instrumentation and modeling provide uniquely practical and cost-effective capabilities for each of the comparisons listed above. The set of comparisons described above is applicable to concrete, composite, pavement preservation and rehabilitation treatments and many other types of pavement structure as has been demonstrated by the California program and many other programs around the world.

However, it must be remembered that there are limitations to APT and APT operators. The ideas for obtaining additional benefits from APT come from the experience of the process of developing a mechanistic-empirical design and analysis method.

One limitation is that APT can be slow. Closed-circuit tracks can take several years to fail several dozens sections with relatively small numbers of traffic repetitions. Fixed devices can take years to fail even fewer sections, although after applying much higher relative traffic repetitions (often through over-loading). Therefore data sets sufficient to provide an adequate range of conditions and structures for development, validation and calibration of comprehensive mechanistic models can take years to develop. These data sets will usually be built by completing a series of experiments that are funded to provide empirical comparisons of different alternatives which are usually the primary focus of APT clients. The additional benefits from these experiments will come from attention to including the following key tasks in each of those experiments:

- Comprehensive laboratory characterization of all materials in the laboratory and field using tests identified as likely to be used for design and analysis in the future.
- Placement and use of instrumentation and other testing of the in-place pavement structure that not only measures realistic responses of value for the empirical comparison desired from an individual experiment but also measurement of responses that will be calculated in mechanistic models. Instrumentation must also not affect the pavement performance.
- First-level analysis of all laboratory and APT data in a timely manner so that inevitable errors (location of instruments, sign of the response, etc) are identified and fixed.
- Systematic uploading of all data into relational databases so that it can be mined many years later.

APT operators and researchers tend to come from the ranks of what can be called “experimentalists” as opposed to “modelers,” and modelers can often be divided into “mechanistic modelers” and “empirical modelers.” Experimentalists are typically most interested in the APT results and the empirical comparison of alternative pavements and which laboratory tests best correlate with those results. Mechanistic modelers are most interested in developing constitutive relations for materials and numerical simulation of the pavement response, and are interested in laboratory tests of fundamental properties (stiffness, damage) as opposed to empirical correlation of “empirical tests” with observed performance. Empirical

modelers like to work with large data sets such as those that come from LTPP and pavement management systems so that they can draw statistically significant results about pavement performance.

There are inherent conflicts and misunderstandings built into these pavement world views. Clients most typically come from the ranks of experimentalists, and consider both types of modelers to be “too academic” and “not practical.” Mechanistic modelers are usually frustrated with the variability of pavements, and the highly complex interactions of the layers. Empirical modelers tend to not want to be bothered with too detailed discussions of the pavement materials and pavement construction, in part because LTPP and PMS data often lack that information because the data collection was intended for network level analysis, and there is a perception that the cost of collecting construction and materials data is too costly for a network or very large experiment (which it is if it is not used).

Despite these built-in conflicts and approaches, the California experience has been that large additional benefits can be obtained from the APT program by involving modelers of both types in the research. They provide insight, they can help solve specific problems of data analysis through modeling of the APT experiment and they can help extrapolate the results to the pavement network in which the APT results are intended to be implemented. Modelers also take away insight from the APT program into their work: mechanistic modelers obtain a much better understanding of the complexity of pavement structures and materials and the role of variability; empirical modelers obtain an understanding of causal relationships between the variables that are in the network database and the importance of variables they may have tended to ignore because of their lack of understanding, particularly materials and construction variables.

Finally, as an operator of fixed APT devices (Heavy Vehicle Simulators), we have made extensive use of data from closed-circuit tracks because of some of the limitation of fixed devices. This is reflected in Figure 2, which shows both types of APT approaches. Data from closed-circuit tracks (Westrack, NCAT and MnROAD) has been used to extend results from HVS testing to provide information regarding faster traffic, variable climate and longer test sections which provide more information about variability (although we are currently modeling HVS test sections as six individual one meter square sub-sections to understand variability as well). The effect of riding quality can not be quantified accurately, using machines such as the HVS as opposed to real traffic on test tracks due to the relatively short pavement sections evaluated, slow wheel speed and the load application method utilized on some devices (controlled constant load levels). It should be noted that Martin and Sharp (7) did measure longitudinal profile and roughness in an ALF experiment, although this is somewhat controversial and not common.

If all APT operators are diligent in collecting and placing their data in relational databases, then data from both can be assembled to solve complex problems that use/overcome the strengths/limitations of fixed APT devices and test tracks. The particular advantages/disadvantages of each type of testing are summarized in Table 2.

In reality, it is suggested that these not be looked at as advantages or negative characteristics but rather as characteristics that are especially for different purposes. For example, during the development of the mechanist-empirical design models it was found that the HVS data generated under carefully controlled and understood temperature and wander conditions, closer observations of performance, and understanding of the wheel position relative to the sensor outputs were very useful for initial validation of the models. The HVS also permitted first level shift factors between laboratory derived damage functions and full-scale

functions. Next, track data from Westrack and NCAT data were used to develop more meaningful shift factors, and also to evaluate the effects of faster trafficking. Currently, field sections are being used to develop better shift factors, now that the mechanisms and models have been established through laboratory testing, simulation and APT, although there is much more uncertainty in the characterization of the materials, trafficking, climate and performance prior to the final observation. It is felt that use of only one of these types of data would have resulted in much less useful models.

TABLE 2 Comparison of Fixed APT devices and Test Tracks

Fixed Devices	Test Tracks
Controlled temperature and moisture	Uncontrolled temperature and moisture
Slow speed trafficking	Highway speed trafficking
Ability to vary load and to overload	Not much ability to overload
Short sections	Longer sections
Controlled wander	More difficult to control wander
Little or no suspension interaction	Realistic suspension interaction
Difficult to measure roughness	Meaningful roughness measurement

Devices that are neither fully fixed nor operating full-scale trucks on tracks, such as those at the LCPC, CEDEX and CAPTIF facilities, offer a mix of the characteristics identified above.

The need for greater links between APT and LTPP must be emphasized again. Long-term performance data combined with some reasonable level of characterization of materials, traffic and climate, is essential for translating models and understanding from laboratory, simulation and APT results to the real world. Long-term monitoring data is also essential to better understanding of variability, both within sections and between sections. PMS performance data connected to project-level materials data and measured values of traffic and climate are essential. However, many PMS databases do not include sufficient links between these data, or data that are precise or complete enough to be useful for calibration of models.

This kind of complete data set can be obtained through construction of full-scale test sections on the mainline as part of normal construction projects, including full characterization at construction, potentially including some instrumentation, and periodic monitoring through the PMS. This was the promise of the federal LTPP program in North America. However, the scale of the experiment and of the database appears to have resulted in less than complete fulfillment of its promise. One of the problems with LTPP is the long time (by definition) to get results. One solution to this problem that would help bridge the gap between APT and LTPP results and also provide early findings from LTPP studies is to perform APT testing on LTPP sections. A plan for this kind of approach (8) was developed for South Africa and considered for implementation for the North American LTPP experiment (9), but was not approved.

STRATEGIC PLANNING FOR APT

The following are a few suggestions regarding areas of research that pavement researchers using APT should investigate more intensively than has occurred to date.

Consideration of variability, both within projects and between projects, should be an area of increasing interest for APT strategic plans, particularly variability due to construction, and the use of recycled materials. Pavement researchers have traditionally focused on deterministic

models for pavement behavior and models and lamented the fact that construction often results in early failure of what should be highly successful designs. It is suggested that APT experiments need to pay greater attention to variability in their experiment designs. This will become more important as the use of recycled materials increases. If 10 or 25 percent of a road project fails, then the entire project is considered failed. It is suggested that much greater attention needs to be paid to the 10th or 25th percentile performance rather than the 50th or 90th percentile. Large pavement contractors and financiers are particularly interested in understanding variability and in viable performance models for innovative contracting methods such as Design-Build-Operate and Build-Own-Transfer contracts.

It is expected that there will be a much greater interest in experimentation on recycled pavements and materials, and new types of pavement structures and rehabilitation techniques that minimize use of virgin materials and energy in this time of rapidly increasing costs and increasing scarcity of virgin materials, and increasing need to reduce energy consumption when producing pavements. The world cannot wait 10 years to have these solutions, and APT again offers unique and cost-effective solutions to rapidly develop new technologies under these changed market conditions.

CONCLUSIONS

From the point of view of an APT operator, one can see that APT has been part of the development of new pavement technology for more than 60 years. APT offers unique capabilities to rapidly move technology from computers and laboratory analysis to full-scale use at attractive benefit/cost ratios. In addition APT offers additional benefits from its ability to attract and focus attention on pavement problems and their solutions.

APT operators must increase their attention to moving results into practice, and documenting both the high costs and much higher benefits of what they produce. There are opportunities to mine APT results to obtain additional benefits if careful attention is paid to fully capturing the results and making them available for later use. Combining of APT results from different types of facilities and with long-term performance data offers additional opportunities for increasing the benefits from APT experiments. Finally, pavement researchers including APT operators must think strategically in terms of the problems they choose to invest in to be sure that they are solving tomorrow's pavement problems, not those of yesterday.

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