100 YEARS TRB
MOVING IDEAS: ADVANCING SOCIETY

CENTENNIAL PAPERS

Standing Committee on Pavement Structural Modeling and Evaluation (AFD80)
Dr. Gonzalo Rada, P.E., Chair

History of the Standing Committee on Pavement Structural Modeling and Evaluation

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HISTORY OF THE AFD80 COMMITTEE

The Committee on Strength and Deformation Characteristics of Pavement Sections (AFD80) has existed since 1970, first under TRB code reference A2K01 (1970 – 1977), then A2B07 (1977-1982), A2B05 (1982 – 2003) and AFD80 (2003 to date). The name was changed in 2016 to "Pavement Structural Modeling and Evaluation."

The list below provides the names of the chairs of the committee:

- Gonzalo Rada, Wood E&IS; 4/15/2017-4/14/2020
- Charles Schwartz, University of Maryland; 4/15/2011-4/14/2017
- Cheryl Richter, Federal Highway Administration; 4/15/2006-4/14/2011
- Judith Corley-Lay, North Carolina DOT; 2/1/2000-4/14/2006
- Tom Scullion, Texas A&M University; 2/1/1994-1/31/2000
- Albert Bush, US Army Engineer Research and Development Center; 2/1/1991-1/31/1994
- Brent Rauhut, Brent Rauhut Engineering; 2/1/1985-1/31/1991
- Amir N. Hanna, Transportation Research Board; 2/1/1979-1/31/1985
- Richard Barksdale, Georgia Institute of Technology; 2/1/1973-1/31/1979
- John Deacon, University of Kentucky; 2/1/1970-1/31/1973

The current committee membership make-up is summarized in Table 1 below—it is full with the exception of one emeritus member slot. The two current emeritus members are Dr. Jacob Uzan and Dr. Marshall Thompson.

Table 1. Current AFD80 Committee Membership Make-up

Slot Name	Current	Allowed	Available
Main Member	25	25	0
Young Member	4	4	0
State DOT Member	2	2	0
International Member	5	5	0
Total	**36**	**36**	**0**
Emeritus Members	2	3	1

SCOPE AND GOALS OF THE AFD80 COMMITTEE

The Committee's current scope statement is as follows:

> *This committee is concerned with the structural modeling and evaluation of pavement sections, including the strength and deformation characteristics of the layers. Areas of interest include transient and permanent deformation, fatigue and fracture as well as load- and environmentally-induced changes in layer characteristics and both destructive and non-destructive test methods for structural assessment purposes.*

Two goals were identified in the Committee's 2017 triannual strategic plan: They are:

Goal 1. Integration of pavement structural condition into the decision-making process at the network level

This goal reflects the emergence of Traffic Speed Deflection Devices (TSDD), which have the capability to collect data at a far higher speed than has been possible in the past, while impeding other highway users or requiring lane closures or traffic control. This enables far greater use of structural data in pavement/asset management than has previously been practical, including project prioritization, repair category assignment and budgeting. The use of structural data at the network level is expected to bring the results of these processes into better accordance with project level decisions, leading to better resource allocation and project scoping. Use of structural data is also expected to dramatically improve forecasting models, enabling better predictions of future condition and assessment of the impact of different funding levels.

Goal 2. Material characterization contributions to pavement design and modeling today and into the future.

The strength and deformation of the layers and materials comprising the pavement structure goes to the heart of mechanistic pavement design and performance modeling, and this goal represents the traditional role of this Committee. This work is closely tied to the work of the pavement design committees, and includes the "push" of design needs driving improvements to testing and analysis, and the "pull" of new data availability driving improvements to design methodologies. Key areas of current interest are field determination of dynamic modulus of asphalt as well as the perennial issue of stress sensitivity of unbound materials. Other active areas are the use of modulus in construction specifications, and the effects of ageing, damage and drainage on modulus.

Because the Committee's past, present and future are tightly knit with the field of deflection data collection and analysis for assessing the structural capacity of pavements, this centennial paper has been written around the history of pavement deflections, which has been a major driver in the Committee's activities.

BACKGROUND ON PAVEMENT DEFLECTION

The first systematic investigator of deflections on in-service pavements was Francis Hveem, who is perhaps better known for his work on asphalt mix designs, the R-value test and the California Profilograph. He started experimenting with deflection measurement devices in 1938, culminating in the installation of 400 deflection measurement devices on 43 pavements throughout California in 1951. This work, along with follow-on work using the Benkelman Beam and California Deflectograph resulted in the Caltrans Tolerable Deflection/Deflection Reduction approach still used today (1). Along the way he explored, but certainly did not solve, complications caused by non-linearity, temperature dependence, loading rate dependence, as well as curl in concrete slabs. Hveem discussed these in a summary of his work to date in 1955, stating "Obviously, the problem of measuring and evaluating pavement deflections refuses to remain simple." (2). This remains true in 2019.

Given these difficulties, one might ask "why bother?" And indeed, from the Caltrans design procedure referenced above, to the AASHTO 1993 design procedure, to the recently-released AASHTO PavementME design procedure there is a pattern of decreasing emphasis on deflection data (indeed AASHTO PavementME barely addresses the maintenance or rehabilitation of existing pavement structures in any respect). This regression is worthy of study, but for the Pavement Engineer there are two basic reasons why deflections will always be of critical importance:

1) Other than thickness, surface deflection is by far the most useful parameter for modeling in-service pavements and predicting their future performance. And unless and until general-purpose pavements are routinely constructed with in-situ instrumentation such as strain gauges, this will remain true.

2) The difficulties in understanding pavement deflections are inherent in all of the responses of a pavement - not just in deflection but also in stress, strain, rate of damage accumulation and ultimately in expected remaining life and rehabilitation necessary to achieve a satisfactory expected life. The deficiencies in our understanding of pavement deflection must be wrestled with, as these same deficiencies affect everything else that the Engineer needs to know about the pavement.

MEASUREMENT APPARATUS: PAST, PRESENT AND FUTURE

BPR

Although as mentioned above, Hveem started measuring deflections on in-service pavements in 1938, the US Bureau of Public Roads (BPR, predecessor to the Federal Highway Administration or FHWA), began performing surface deflection measurements on concrete pavements at a test facility then known as the Arlington Experiment Farm (now known as Turner-Fairbanks Highway Research Facility) a few years earlier (3). The purpose of this testing was to validate Westergaard's theory, which is still widely used for modeling concrete slabs. This testing confirmed Westergaard theory for center slab and joint loading conditions, but showed some deviations for the corner slab loading condition. The Spangler corner equation was developed to fit this data, and was later incorporated into the design equation and nomographs published in the 1972 AASHTO Interim guide (as well as the 1986 and 1993 Guides) as a way to extrapolate the AASHO road test data to different subgrades and concrete mixes (4).

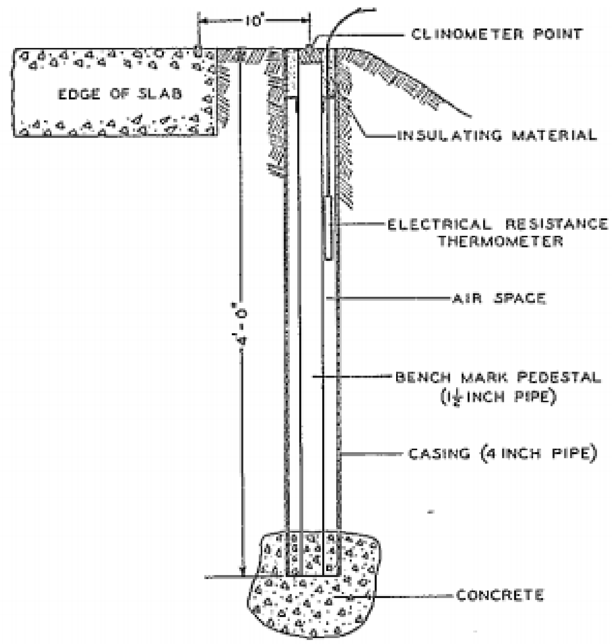

Figure 1. BPR Clinometer, after (3)

The BPR apparatus is unusual in that it used a clinometer to measure the shape of the deflected slab at 10 inch intervals, with a reference benchmark set off to the side of the slab, as shown in Figure 1. The deflected and undeflected profiles of the slab were calculated by integrating the clinometer data (with the benchmark as the zero deflection boundary condition), in a manner similar to the Traffic Speed Deflectometer (discussed below). Loading was accomplished using a semi-static load frame.

Hveem

Hveem's original deflection measurement apparatus consisted of a vertically-referenced Linear Variable Deflection Transducer (LVDT), which measured the distance between the pavement surface and a steel rod driven into the subgrade. Continuous readings were recorded on photographic film, allowing small changes in surface elevation (i.e. deflections) due to the passage of live traffic to be measured. This apparatus is shown in Figure 2. Starting in 1951, over 400 of these devices were semi-perminantly installed in 43 different in-service pavement sections located in California (1).

Hveem experimented with various factors, including the depth at which the reference rod was set, pavement temperature, pavement structure, pavement condition, traffic speed and axle configuration. While discussions of these effects were published, the design procedure developed based on this data only included traffic, pavement thickness and maximum surface deflection as parameters.

The drawback of this apparatus is evident – it is expensive to purchase and install, and is therefore not suited to use in a typical pavement design project, especially one that attempts to account for the spatial variblity across a typical-sized pavement maintenance project. Starting in 1954 data from these devices was supplemented by Benkelman Beam data, and in 1960 with California Deflectograph data (5).

Benkelman Beam

The Benkelman Beam is named after A.C. Benkelman, a research engineer with the BPR, who from 1952 to 1954 participated in the WASHO road test (a predecessor of the more well-known AASHO road test). The Benkelman Beam was developed during the course of the WASHO road test – initial deflection data from the test was collected using vertically-referenced LVDTs, similar to that used by Hveem (6).

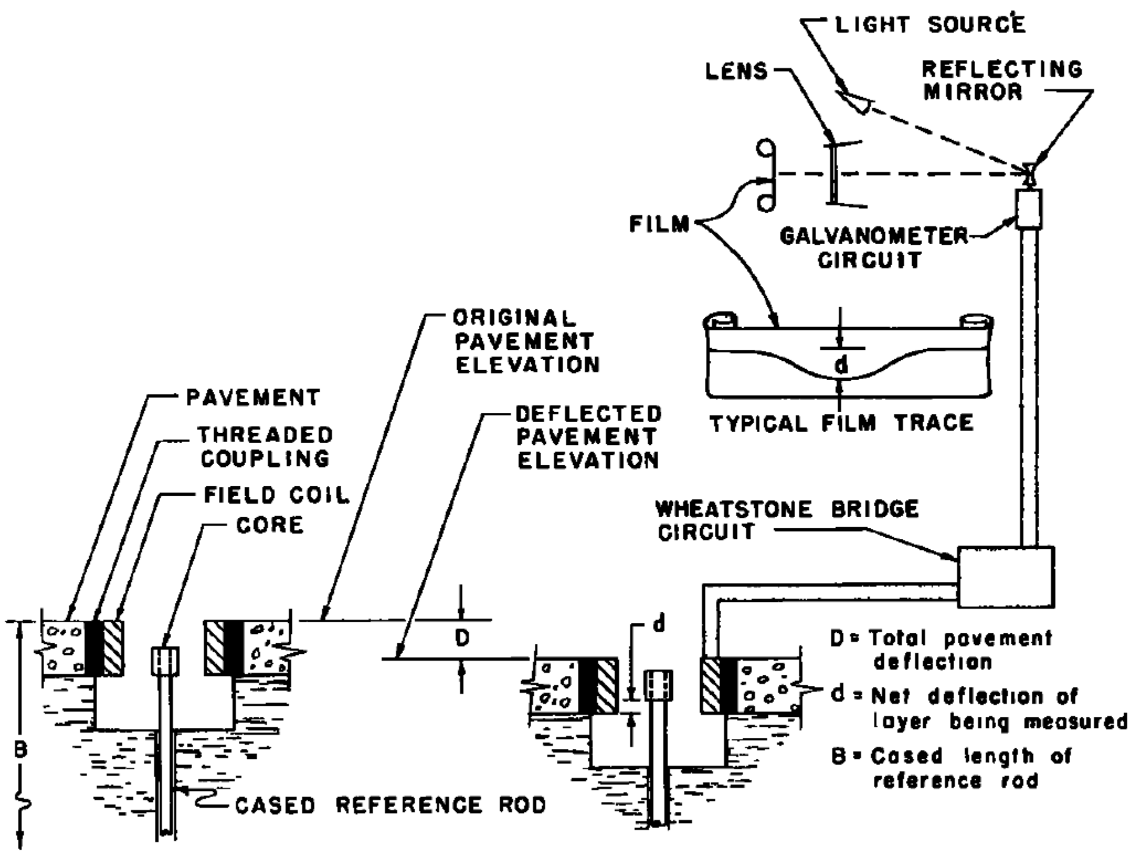

Figure 2. Hveem Deflection Apparatus, after (1)

In contrast to previously used vertically-referenced devices, the Benkelman Beam uses a laterally offset reference point, as shown in Figure 3. The beam is designed so that the tip can be placed between a set of dual truck tires as shown in Figure 4. The deflection is typically then measured as the truck moves away and the pavement rebounds.

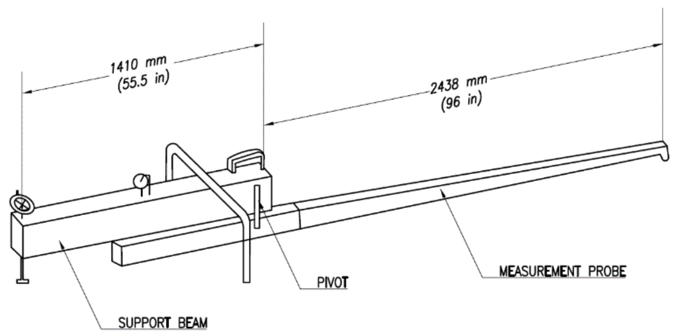

Figure 4. Benkelman Beam.

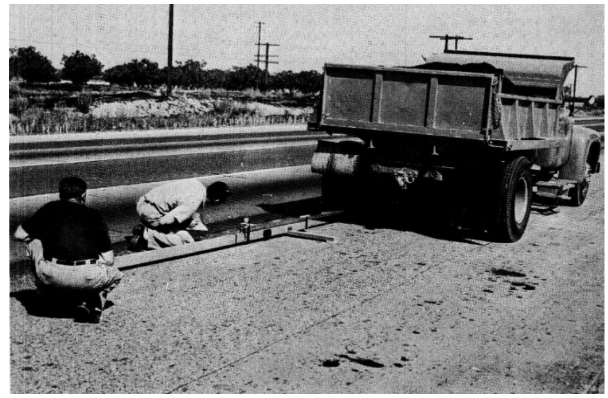

Figure 4. Benkelman Beam in Use, after (1)

As of 2019, there are still several manufacturers of Benkelman Beams, and the purchase price is a small fraction of the more sophisticated devices listed below. Obvious drawbacks include a very slow speed of operation, the requirement of a multi-person crew (typically three), and a heavily loaded truck (typically 18,000 pounds on the rear axle in the US or 10 metric tons outside of the US). Less obvious drawbacks include that it is very cumbersome to measure deflections other than the maximum deflection, the support legs are typically not fully outside the deflection basin and the loading condition is much slower than live traffic. Of these drawbacks, the slow speed of data collection has attracted the most attention, and attempts to create a moving Benkelman Beam started almost as soon as it was invented.

Deflectographs / Traveling Deflectometers

Several types of deflectographs have been developed using a traveling Benkelman Beam principal. While the mechanical details vary, the general concept is the load is generated by a vehicle that creeps along at a constant speed in the range of 0.5 to 2 mph (1 – 3 kph). This vehicle also carries a measurement frame which is automatically placed on the pavement, and remains stationary on the pavement for a period of time while the vehicle creeps forward and then is lifted up and moved forward to catch up with the vehicle. The measurement frame holds one or more Benkelman Beam type measurement levers.

Deflectograph prototypes were under development in the US and France starting in the mid 1950's. The Caltrans unit (shown in Figure 5) was operational from 1960 and the Lacroix Deflectograph was operational from 1964, with some examples still in use in 2019. Deflectographs using the same principal were developed in Denmark and the UK shortly thereafter. A similar device is the Curviameter, which was developed in 1977. The Curviameter uses geophones for deflection measurement, which allow a significantly higher speed of approximately 11 mph (18 kph).

Figure 5. California Traveling Deflectometer, after (5)

While deflectographs were used and continue to be used widely in Europe, in the US use was limited to Caltrans, and even that unit was quickly supplanted by Dynaflects except in a few research roles. It should be noted that while deflectographs test while moving, they still move much slower than typical traffic speeds and require traffic control on all but the lowest volume roads.

Vibratory/Dynamic Deflection Devices
Shell Oil experimented with using a heavy vibrometer truck originally developed for seismic exploration in the Netherlands from the 1960s. The Dynaflect, shown in Figure 6, was first produced in 1964 by Lane-Wells, a US oilfield services company better known for "gun perforation" of under-producing wells, and a forerunner of modern fracking techniques (7). As an affordable, convenient and off-the-shelf device, the Dynaflect quickly became widespread amongst highway agencies and private consultants in North America, although adoption was limited in the rest of the world. As of 2019, the Dynaflect is out of production although some are still in regular use.

Figure 6. Dynaflect, after (7)

The Dynaflect included two major advances over previously available devices. The first is that the pavement loading was generated by a dynamic force (in this case the oscillation of an eccentric weight), meaning that the device could be mounted on a small trailer pulled by a regular passenger vehicle. Previous devices relied on the static weight generated by heavily loaded truck, requiring a commercial driver's license to operate and other inconveniences.

The second advance is the use of geophones to measure pavement deflections. Previous devices directly measured the change in elevation of the pavement surface relative to a vertically or horizontally offset reference point. Obtaining a reference point fully outside of the deflection basin is challenging, and ultimately becomes a compromise between the degree of load influence at the reference point and size of the apparatus. In contrast, a geophone uses an inertial reference, essentially referencing a point to itself over time and eliminating the need for a spatially offset reference. A drawback of geophones is that they do not directly measure displacement, and a mathematically complex transform is required in order to compute pavement deflections. Calibration of the geophones is also more complex than direct displacement measuring devices.

An obvious drawback to the Dynaflect is its low maximum loading of 1,000 pounds peak-to-peak. A less obvious drawback is its fixed 8 Hz frequency of loading, which may or may not be a particularly relevant frequency for pavement design. Larger devices such as the RoadRater and the Texas Transportation Institute (TTI) Rolling Dynamic Deflctometer (RDD) had significantly higher maximum loads as well as variable loading frequency. Variable loading frequency highlighted the sensitivity of pavements to loading frequency, but at the time there was no way to utilize that information for practical purposes or even determine which frequency is the most relevant. As of 2019, dynamic deflection devices have been almost entirely superseded by falling weight deflectometers (FWD).

Falling Weight Deflectometer

Falling weight deflectometers (FWDs) use a very similar measurement technique to dynamic deflectometers (geophones or seismometers), but have a different means of load generation. FWDs generate load by lifting and dropping a large mass on to the pavement. This is a more efficient means of generating load, enabling units with a maximum peak load of up to 60,000 pounds that can still be towed with an ordinary passenger vehicle. Perhaps more importantly, the load pulse can be shaped to simulate the load imparted to a pavement by a moving wheel, which enables the question of frequency dependence to be side-stepped (or at least ignored for routine evaluation and design purposes). Different devices do have slightly different load pulse durations, which has been noted as a source of reproducibility errors.

The early development of FWDs was mostly performed in France, starting in the late 1960s. Production FWDs were developed in Denmark and commercially available from 1978 (8). Other than the electronic data acquisition systems, subsequent development as of 2019 has been largely limited to the mechanical means of dropping and catching the weight, including electromagnetic systems, catchless hydraulic or most recently catchless ballscrew systems.

The FWD remains limited by the fact that the device collects data while stationary. This limits the rate of data collection such that network-level testing is impractical, and project level testing remains subject to tradeoffs regarding cost of data versus coverage (to some degree this can be said to be true for all data collection efforts, but the spatial variability of pavements versus the funds available for engineering services is in a particularly sensitive range). Stationary data collection also typically imposes traffic control costs, not to mention external user-costs, including time-delay and increased risk of accident. Direct costs of traffic control can equal the cost of data collection on even relatively low-volume facilities. On urban arterials and busy airfields these external costs can rise to the point where no stationary pavement data collection is practical, regardless of the benefit. This is a problem that extends far beyond deflection testing, and can result in a paradoxical inverse relationship between the value of a facility and the quality of the data used in its design.

Traffic Speed Deflection Devices

As has been described above, no sooner did the Benkelman Beam appear that attempts were made to make it collect data while moving. The difference between the deflectograph and the curviameter represented an order of magnitude improvement, but still remained an order of magnitude below what was necessary to blend with traffic and to eliminate traffic control and external costs such as user delay. A well-known external cost includes a fatal accident involving the Danish Deflectometer, which directly lead to the development of the Greenwood Traffic Speed Deflectometer (TSD). The desirability of a device to collect data while traveling at the same speed as prevailing traffic was obvious, but technology had to catch up.

The development of laser-based pavement surface profilometers sparked and interest in using the same technique to measure pavement deflection due to a moving wheel load. This approach immediately ran into difficulties related to the small scale of pavement deflections relative to surface texture variability. Development of a US device initiated with consecutive funding from Ohio DOT, the US Air Force, Federal Aviation Administration, and Federal

Highway Administration. This device has gone through multiple incarnations, and has recently changed from a laser triangulation technique to a camera parallax technique. In addition to the difficulties in measuring deflection at highway speeds, the sequence of funding agencies reflects the difficulty of inducing sufficient deflections on airfield pavements with a device that is legal to traverse highway pavements. It also reflects the importance of minimizing disruption to critical infrastructure. As of 2019, one unit has been produced, and is owned by the manufacturer

Separately, the Danish Road Directorate funded a project to replace the Danish Deflectograph, using doppler lasers to measure pavement deflections. This project resulted in the Traffic Speed Deflectometer. Use of doppler lasers resulted in a system more resistant to surface texture variability, but introduced the problem of converting pavement surface velocities to pavement surface deflections. Several approaches to this problem have been published so far, developed by both manufacturer and users, including model fits and numerical integration. As of 2019, 14 units have been produced and sold primarily to international government agencies. One is owned by a consulting firm in the US.

Finally, a competing device called the RAPTOR. This device includes several linescan lasers at different distances from the loaded wheel. The deflection basin is computed by overlaying the data from these devices using image recognition techniques. To date, one unit has been produced and demonstrated in Europe in 2018, and then brought to the US at for demonstration at the TRB 2019 annual meeting.

DATA ANALYSIS: PAST, PRESENT AND FUTURE

In some ways, the analysis of deflection data significantly pre-dates the collection of pavement deflection data. Boussinesq (a French mathematician, more famous for his contributions to hydrodynamics and the study of turbulent flows) published his equation for deflections in a uniform half-space in 1885, about 40 years before any serious attempts at pavement deflection data measurement. This equation is still often used for computing pavement moduli based on impulse loads, despite the fact that it was intended for evaluating building foundations under static loads. This equation is especially common in the context of lightweight deflectometers, soil stiffness gauges, and stiffness-based density gauges. A form of the Boussinesq equation is included in the 1986 and 1993 AASHTO Guides, albeit in disguised forms and with hard-coded Poisson's ratio terms.

Interestingly, neither Hveem nor Benkelman in their pioneering work on pavement deflections discussed a concept of a mechanistic theory linking these deflections to fundamental properties of the pavement system. Hveem did develop a concept of "tolerable deflection," which is the maximum deflection at the center of a 9,000-pound wheel that a good-performing pavement can be expected to exhibit. Hveem published tables of tolerable deflections for different pavement types (rigid, semi-rigid and flexible), thicknesses and traffic levels, and these tables are still used by Caltrans for the design of semi-rigid and flexible pavements (1). Other design methods (mostly obsolete) using similar concepts include Asphalt Institute MS-17 (9) Canadian Good Roads Association (10) and the UK (11).

In addition to maximum deflection, a variety of basin shape factors have been defined, consisting of the result of basic arithmetic operations performed on deflections measured at two or more offsets from the center of the load. Of particular note are the Surface Curvature Index

(SCI), which is relatively sensitive to the surface layer properties in flexible pavements, and the AREA parameter which is relatively sensitive to the radius of relative stiffness of rigid pavements.

As mentioned above, mechanistic analysis of deflection on rigid pavements started in the 1930's with the use of deflection to validate Westergaard theory. Since then, relatively straight-forward methods of estimating Westergaard parameters (including slab modulus and modulus of subgragde reaction) using deflection data have been developed, including the AREA based methods described in the AASHTO 1993 Guide and 1998 Supplement, and backcalculation approaches developed by Ionnides and Khazanovich, now known as "Best Fit" (12).

Layered elastic theory of a form suitable for flexible pavements was developed by Burmister, starting in the early 1940s (13). A two-layer simplified version of this model is included in the AASHTO 1993 guide, however the multi-layer solutions remained impractical until implemented as computer programs, starting with the CHEVRON program in 1963 (14). Chevron (then officially known as Standard Oil Company of California) donated the source code to Universities and public agencies, asking only for recognition and acknowledgement in return, resulting in its use in many other derivative works. Other early layered elastic programs include BISAR (Shell Oil) and WESLEA (US Army Corps of Engineers). Application of layered elastic theory to backcalculation of elastic moduli from surface deflections using computers was reported in 1971 by Scrivner, describing a two-layer only program called ELASTIC MODULUS, a direct forerunner of TTI/TexDOT's MODULUS program (15). Irwin (16) and Ulliditz (17) independently described multi-layer backcalculation in 1977.

Since then, minor updates to layered elastic backcalculation have been made, including methods for estimating depth to bedrock, performing temperature correction for asphalt, and estimation of non-linear properties of unbound materials.

Dynamic backcalculation has been an area of study since at least the late 1990's, with multiple avenues of investigation ultimately proving unfruitful due to limitations of theory, computer processing power and deflection data time histories. Ongoing work, including that by Chatti (BACKLAVA) and Lee (Viscowave), is highly promising although much work remains to be done before implementation can occur (18).

MAJOR ACCOMPLISHMENTS OF AFD80 COMMITTEE

The Committee typically sponsors or co-sponsors two podiums sessions, one poster session, and two workshops at the TRB Annual Meeting. Each podium session includes four presentations related to pavement structural evaluation or modeling, while the poster sessions typically include around ten presentations. As an example, the list of committee activities over the past two plus years (2018 and 2019) are listed below:

Podium Sessions

- 2018 Session 275 "Pavement Structural Modeling and Evaluation."
- 2018 Session 748 "Network-Level Pavement Structural Evaluation."
- 2019 Session 1112 "Network Level Evaluation using TSDD."
- 2019 Session 1183 "Pavement Structural Evaluation and Modeling."

Poster Sessions

- 2018 Session 388 “Pavement Structural Modeling and Evaluation.” (11 posters)
- 2019 Session 1556 “Modeling and Evaluation of Pavement Structures.” (9 posters)

Workshops
- 2018 Workshop 163 “Next-Generation Pavement Management Systems: Incorporating Network-Level Structural Capacity Leading Indicators.”
- 2018 Workshop 172 “Integrating Geotechnical Instrumentation and Modeling to Optimize Performance of Transportation Infrastructure” (with AFS20 with AFD80).
- 2018 Workshop 878 “Pavement Performance Data Analysis” (with AFD20).
- 2019 Workshop 1067 “Use of Traffic Speed Deflection Device Data in Network and Project Level Pavement Decisions.” (TRB e-circular presently undergoing review by TRB).
- 2019 Workshop 1794 “Pavement Performance Data Analysis” (with AFD20).

Webinars
- June 8, 2017 “Use of Traffic-Speed Deflection Devices in Network-Level Pavement Management Applications.” (with AFD20)
- August 21, 2017 “New Pavement Engineering Technologies - The Long Term Pavement Performance Climate and Bind Tools.” (with AFD20)
- October 23, 2018 “Designing Pavement Subsurface Drainage Using DRIP Software.” (with AFS60)
- April 23, 2019, “Evaluation of Superheavy Load Movement on Flexible Pavements. (with AFS50)

Also, each annual meeting of the AFD80 committee typically hosts two to four technical presentations which are not included as part of the TRB Annual Meeting general podium or poster sessions. Attendees at each annual meeting of the Committee range from 60 to 125 professionals.

In addition to the above named activities, perhaps the most critical one and the one that involves the most committee members is the annual paper review process. Table 2 summarizes the number of papers that have been reviewed by the committee in support of the 2014 through 2019 TRB meetings—typically each paper is assigned to 5 committee members or friends of the committee for review. The table also shows the number of papers that have been recommended for presentation and those that have been recommended for publication in the Transportation Research Record journal.

Table 2. Paper Review Summary Statistics

Year	Reviewed	Presentation	Publication
2014	25	12	5
2015	22	13	4
2016	15	9	3
2017	48	27	9
2018	32	20	6
2019	**29**	**17 (of 29)**	**5 (of 27)**

The committee also has one subcommittee known as the "Mechanistic Characterization of Pavement Layers Subcommittee." This is concerned, in support of the main committee, with the analysis and determination of the engineering parameters (e.g., layer and material mechanical properties) related to the pavement system topology, loading complexity, and environmental variability. The focus is on new non-destructive testing, measurement techniques and devices, types of data and data fusion, modeling, and interpretation techniques that advance the state of practice.

There were approximately 20 participants at the last subcommittee meeting and discussions centered on standardizing traffic speed data collection and analysis, which is an emerging field with little standardization and data are still very device-specific. As a results of those discussions, the subcommittee is contemplating the following three general areas: 1) focus on pavement management systems (PMS), 2) improve mechanistic understanding of pavements especially with regards to wave propagation, and (3) explore side-effects of vastly increased spatial data collection, perhaps with regards to damage assessment.

Lastly, each year the committee has drafted approximately two NCHRP Research Needs Statements to be considered for agency sponsorship and funding. Because funding has not been realized the past couple of years, the Committee has embarked in the development of a RoadMap to more effectively and efficiently address research needs.

SUMMARY

The Committee's traditional focus area on the strength and deformation characteristics of pavements remains as vital as ever. Several key problems identified by Hveem in 1955, including loading rate and temperature dependency as well as stress sensitivity, have continued to challenge researchers and frustrate practitioners, however work is in progress that promises significant advancement.

Additionally, advancements in data collection technology have opened important new opportunities for the use of structural data in the field of pavement management. The Committee is expected to play a key role in guiding research and implementation in this area, including data collection guidelines as well as improved condition forecasting models and decision making tools.

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