# Traffic Flow Theory and Characteristics Centennial Paper (DRAFT)

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The TRB Committee on Traffic Flow Theory and Characteristics (TFTC) is concerned with the development, validation, and dissemination of theoretical, experimental, methodological, and applied research on traffic flow theory (TFT) and traffic flow characteristics (TFC), and the determination of the relationship of TFT and TFC to the planning, design and operation of transportation systems. Such systems are undergoing rapid transformation due to the introduction of new technologies, mobility services and modeling paradigms. This provides new options for traffic monitoring and control that makes it possible to envision more safe, efficient and sustainable traffic operations. The TFTC committee research challenges are in line with this new era in transportation.

To mark the passage of the centennial, all TRB committees have mounted special efforts to capture the current state of the art and practice and their perspectives on future directions in their respective areas of focus. This paper begins with a review of the important evolutionary changes that have occurred in the field of TFT since the inception of the TFTC Committee in 1963. With the guideposts defined by this history, new paradigms of TFT and a vision of future directions are presented.

## MILESTONES

The TRB Annual Meeting and associated TFTC committee meetings play a leading role in facilitating scientific exchange in the traffic flow theory community. Even as traffic processes and phenomena are better understood and more readily characterized through the availability of high resolution sensor data and advanced computing capabilities, the fundamentals are just as important today as in the early days. They form the foundation for all the theories, techniques, and procedures

that are being applied in the design, operation, and development of advanced transportation systems. (*1*)

This section describes the principal milestones or accomplishments in the field of TFT that define the current state of the art. Historically, TFT has sought to describe the interactions among vehicles, drivers, and the infrastructure in a precise mathematical way (*1*). These descriptions have often been linked with empirical observations; however, some part of the literature pertains to models of system components that were not directly observable in order to improve our general understanding about their functioning. As generally conceived, the infrastructure consists of the surface transportation system, although communication layers are becoming increasingly integrated with the transportation system. These theories are an indispensable element of all traffic models and analysis tools that are being used in the design and operation of streets, highways, and urban systems.

The conceptualization of traffic as a science began in the 1930s with the first empirical data collection efforts and subsequent application of probability theory to the description of road traffic. This empirical thread has been woven through the developments in traffic science until today. The pioneering empirical studies conducted by Greenshields (*2*) led to a simple model relating vehicle flow and travel speeds, and the investigation of traffic performance at intersections. The expansion of the highway system and tremendous increase in automobile use after World War II led to a surge in the study of traffic phenomena, with notable empirical efforts led by Edie and others involving the Lincoln Tunnel in New York. (*3*, *4*) Along these lines, Wardrop also contributed to the scientific approach to transportation phenomena (*5*).

In 1959, Herman organized the International Symposium on the Theory of Traffic Flow (*6*). This was the first of what has become a series of symposia on the theory of traffic flow and transportation science (2019 will see the 23rd edition). Tracing the topics covered in the 22 proceedings of these symposia indicates the tremendous developments over the last 60 years in the understanding and the treatment of traffic flow processes. These proceedings also reflect exciting developments beyond the highway mode and involvement of researchers from many disciplines and countries around the world. (*6*)

In 1964, the Highway Research Board published the Monograph on Traffic Flow Theory as HRB Special Report 79 (*7*). Another version of the monograph was published in 1975 (*8*) and revised in 2001 (*9*). The latest monograph contains eleven chapters, the subjects of which are good indicators of the major progress in the understanding of TFT in the second half of the 1900s:

1. Introduction
2. Traffic Stream Characteristics
3. Human Factors
4. Car Following Models
5. Continuum Flow Models
6. Macroscopic Flow Models
7. Traffic Impact Models
8. Unsignalized Intersection Theory
9. Traffic Flow at Signalized Intersections

Review of several recent summaries of the development of the field of TFT (*10–12*) and leading scholars in TFT revealed that certain developments in the history of traffic theory stand out above the others.

**Macroscopic Flow Models**

Greenshields' pioneering work on empirical macroscopic flow relations (*2*) helped establish a scientific perspective toward traffic. The recognition of the similarity between traffic flow and compressible fluid, led to macroscopic traffic flow modeling based on application of hydrodynamics. In particular, the hydrodynamic models developed by Lighthill & Whitham (1955) and Richards (1956), referred to collectively as LWR models, and their enhancements serve as a guidepost in the history of traffic theory (*13*, *14*). Newell's simplified kinematic wave theory is also considered as a significant development of traffic theory (*15–17*). The monograph by (Nobel laureate Ilya) Prigogine and Herman (*18*) introduced gas-kinetic theories of traffic flow using approaches from statistical mechanics, providing the basis for more recent work including mesoscopic and cellular automata models. The discretization of the LWR formalized by Daganzo's cell transmission model (*19*, *20*) was incorporated in simplified dynamic traffic assignment and network models. The development of "higher order" flow models, starting with Payne (*21*), Daganzo's criticism (*22*), and subsequent rebuttal (*23*), further serve as milestones in traffic flow history. Extensions of this work more recently in the physics research community have included development of a three-phase hypothesis, including the consideration of a synchronized flow state (*24–26*). Daganzo (*27*, *28*) introduced a variational theory of traffic flow (also known as viability theory in other fields), which helped unify different traffic presentations (macroscopic, microscopic and mesoscopic) under the single umbrella of first-order conservative flow motion (*29*, *30*), revisit the numerical solution of the LWR model, and make connections between local and global traffic states using robust averaging methods.

**Microscopic Flow Models**

As a foundation for the more popular modeling approaches, the recognition of the similarity between traffic flow and moving particles led to the development of microscopic car following models (*31*) (*32*). This included the recognition of the importance of human factors in traffic flow modeling, which led to microscopic traffic flow modeling based on car-following, lane-changing, and gap acceptance behaviors. Notable families of subsequent car following models include: *Stimulus Response Models* (*33*, *34*), *Collision Avoidance Models* (*35–37*), *Psycho-Physical Models* (*38–49*), the *Optimal Velocity Model* (*50*), the *Intelligent Driver Model* (*34*, *51*), and *Cellular Automata Models* (*52*). Extensions to the macroscopic and microscopic perspectives have led to hybrid traffic flow models (*53*, *54*). With the development of autonomous vehicle technologies, car-following models have been extended for vehicle control, such as adaptive cruise control (ACC) (*55–58*) and cooperative adaptive cruise control (CACC) with the latter accounting for communication and cooperation among vehicles (*59–65*). Along with these technologies, platoon stability analysis rooted in car-following models has also gained new research interests (*56*, *60*, *62*, *63*, *66–70*).

**Data and Simulation**

The third set of accomplishments in the field of TFT are related to the advancements in sensing and computing that have led to improved empirical analyses and simulation techniques. These efforts have been inspired in part by the early empirical efforts of traffic science pioneers (e.g., (*71*)). The I-880 field experiment was one of the first studies to produce a comprehensive database of field data from multiple sensors and incident characteristics (*72*) and was among the earliest empirical traffic data sets made available online. The Berkeley Highway Laboratory (BHL) built off of the I-880 field experiment by combining per-vehicle loop detector data with video monitoring (*73*). In the subsequent years, many archival data management systems (ADMS) that provide conventional aggregated detector data along with data analysis and visualization for large highway networks have become available online (e.g., California Freeway Performance Measurement System (PeMS) (*74*)). ADMS are a common source for input, calibration, and validation of traffic models.

While the detector data from those efforts provide a wealth of macroscopic traffic data, a great need remains for additional microscopic traffic data to develop, validate and refine theories and simulations. Orthorectified imagery is the most direct means of collecting such data over many vehicles and large distances. An early example of such work is by Treiterer (*75*, *76*) which used airborne imagery to track 209 vehicle trajectories over 3 miles of freeway. Turner-Fairbank Highway Research Center used a similar technique to collect vehicle trajectory data in the 1980's (*77*). These needs were widely recognized and the FHWA-sponsored Next Generation Simulation (NGSIM) project collected such data from tall buildings adjacent to busy roadways, including the pre-existing camera deployment in the BHL (*78*). The NGSIM data is the largest set of empirical microscopic data set on vehicle movements and interactions that exists to date, and is considered as the best resource for simulation model developers, traffic flow theorists, and data analytics researchers. However, there is growing evidence of systematic errors in the NGSIM data sets, e.g., (*79–81*). Instrumented probe vehicles have been another source of microscopic traffic data and used to study aspects of microscopic traffic flow since the 1950's, e.g., (*31*, *82–85*). Regardless, the existing microscopic data sets combined only comprise a few hours of traffic and there is a greater need than ever for highly accurate empirical microscopic data.

Perhaps the most widely recognized and used products related to TFT by transportation system engineers and planners are different levels of simulation models (macroscopic, mesoscopic, and microscopic). Development of simulation models can be traced to the 1970s with increasing utilization in the 1980s. Commercially available products became available through the years, and most transportation system projects that involve traffic analysis are currently required to use simulation for analysis. As technology advances, traffic simulation is playing an increasing role as a problem-solving tool for transportation system analysis. Researchers and practitioners are realizing the urgent need for updating the underlining algorithms with emerging technologies, including connected and automated vehicles. This is reflected by the recent surge in research and development on this subject.

In 2008, the TFTC Committee began a series of biennial summer conferences. At a 2012 summer conference, held jointly between TFTC with the HCQS Committee, a major outcome was to move forward jointly to create a Transportation Simulation Manual (TSSM) to detail the state of the practice in transportation simulation. The first version of this manual has been developed and is expected to be released in 2019.

**Traffic Phenomena: Capacity Drop and Stop-and-Go Traffic**

Decades of research have been devoted to understanding two major freeway traffic phenomena: 'capacity drop' and stop-and-go oscillations. The capacity-drop phenomenon has been observed by many empirical studies, wherein bottleneck discharge rates diminish by 5-30% after the queue onset near merge bottlenecks (*86–91*), diverge bottlenecks (*92, 93*), weave bottlenecks (*94, 95*), uphills, or sags (*96, 97*). Numerous theoretical and empirical studies suggest that capacity drop arises due to car-following behavior (*98–102*) and disruptive lane-changes (LCs) (*53, 103–106*), including LCs downstream of the apparent bottleneck (*107*) and driver relaxation after LC maneuvers (*108–110*). Along with empirical observations, substantial modeling efforts have been made to obtain insights into and reproduce the capacity-drop phenomenon by identifying its causes, such as traffic voids caused by bounded acceleration or LC vehicles (*53*) or occupying multiple lanes simultaneously (*111, 112*).

In stop-and-go traffic (often referred to as traffic oscillations), vehicles exhibit oscillatory trajectories with regular deceleration/acceleration cycles. These disturbances were typically found to form near active freeway bottlenecks (*113*), propagate against congested traffic flow at relatively constant speeds of 10-20 km/hr (*25, 114–118*) and often grow in amplitude as they propagate (*114*), though depending on geometry, the disturbances may also attenuate (*119*). Stop-and-go traffic and capacity drop phenomena are closely linked as the latter is related to the generation of the former. This phenomenon was first reported in the late 1950s (*87*), but its mechanisms were not understood very well until high resolution data became available in the 2000's. Several later studies based on empirical microscopic data revealed that oscillations formation and growth are caused in part by LCs (*113, 114, 120–123*) and in part by driver characteristics (timid vs. aggressive) (*121, 124*). An experiment on a test-track by Sugiyama et al. (*125*) showed that stop-and-go disturbances can emerge spontaneously due to instabilities in car-following, confirming the phenomenon referred to as "phantom bottlenecks". There have been extensive modeling efforts to describe oscillations in the form of car-following stability analysis (*126–129*), probabilistic driver behavior (*130, 131*), introduction of new traffic regimes prone to disturbance generation (*132, 133*), and time-varying driver characteristics (*124, 134*).

**Active Modes and Crowd Behavior**

While walking is undoubtedly the oldest mode of travel, only in the second half of the previous century have its properties become the subject of scientific investigation. Most initial work has consisted of guidelines intended for the planning and design of sidewalks, stairways and terminals. Relations similar to the fundamental diagrams of vehicular traffic flow have been established for pedestrians along walkways and stairways. Just as vehicular traffic, pedestrian flows exhibit similar characteristics of decreasing average speed at higher densities, with decreasing throughput beyond a certain density level. However, pedestrian flows at higher densities differ markedly from vehicular traffic because of the multidirectional nature of the interactions, and the greater compressibility of human flows relative to vehicular flows. With the increase in size and occurrence of serious accidents in connection with large-scale gatherings (concerts, games, pilgrimage, political rallies, and so on), considerable attention turned to modeling crowd behavior and associated flow processes. Theoretical models have been coupled with observation, and a class of simulation tools have emerged to support the planning and design of pedestrian facilities and management of large-scale events, including emergency evacuation. Notable contributions include

Helbing's social force model (*135*) and characterization of three phases of crowd behavior (*136*) (based on data collected at the Muslim pilgrimage in Makkah), Hoogendoorn and Bovy's gas-kinetic models (*137*), and Mahmassani and co-workers' Hajj simulation models (*138–140*). Many contributions based on experimental observation have also been developed, including the extensive work conducted at TU-Delft in Hoogendoorn's group (*141, 142*) , and by Seyfried (*143*), and more recent analogies with ants and other animals (*144*). This interest has led to the establishment of a Crowd Dynamics and Modeling Subcommittee of the TFTC Committee, which has sponsored several sessions and workshops at the TRB Annual Meetings.

Along with greater interest in walking, urban dwellers are constantly encouraged to use active modes for local travel, particularly bicycles, but more recently also including electric scooters. Bicycle traffic science remains in its infancy, with scattered contributions over the past two decades (e.g. (*145*)).  A more recent European effort at TU-Delft is helping address this gap (*146*). With increasing heterogeneity amongst roadway users in urban environments, it is expected that the topic of mixed traffic flow will gain considerable attention in the coming decade.

**Traffic Control**

The primary form of traffic control applied by transportation agencies consists of traffic signals that allocate the shared right of way to alternating conflicting approach movements. Traffic theories for signalized intersections were derived from queueing models, and analytical expressions for delay at intersections sought to capture the effect of signal timing parameters on intersection delay. A good summary of this work is presented in a 1974 textbook by the late Gazis (*147*), as well as in a Chapter of the Traffic Flow Theory Monograph (*9*). Microscopic traffic simulation tools have gained wide acceptance in the evaluation of signalized intersections in the process of developing timing solutions.

For freeway traffic, early control attempts were all based on ramp metering under presumed steady state conditions. More realistic formulations were developed in a control theoretic framework, where the system model relating control variables to state variables is based on a higher-order continuum model of freeway traffic such as Payne's (*148*) and Papageorgiou's (*149*); Hadj-Salem and coworkers presented a comprehensive application of dynamic ramp metering using local feedback control (*150–152*) to the Boulevard Peripherique in Paris.

Mainline control attempts emerged primarily in Germany, with the main form of control consisting of dynamically displayed speed limits, intended to delay the onset of flow breakdown. The scientific underpinnings of these models were primarily due to Kühne (*153*) and his coworkers, who showed that adding a viscosity term to the dynamic speed density relation could produce stop-and-go waves, though these models were not essential to the implementation of the control strategy. More recent developments in flow breakdown control are also based on speed limitation, coupled with sophisticated sensing and control display technologies (*154–156*). Significant new opportunities for effective freeway control are possible with emerging new technologies such connected and automated vehicles (*157–159*).

At the network or system level, predictive management strategies have been proposed, using simulation-based traffic estimation and prediction systems that rely on mesoscopic flow models that integrate real-time sensor data with historical information (*160, 161*). With additional

deployment of connected and autonomous vehicles, the significance of these tools will increase, with additional improvement coming from selective application of machine learning techniques.

**Human Factors**
Incorporating human factors into traffic flow modeling has been challenging. However, limited studies have incorporated the following human dimensions in operational and tactical driving maneuvers: 1) risk-taking; 2) cooperation; 3) learning; 4) impatience; 5) aggressiveness; 6) distraction; 7) experience; 8) and uncertainty (*162*). Such human dimensions are essential as they are arguably the main contributors to collisions, and most traffic flow models are collision-free up to this day.

Van Lint and Calvert (*163*) offers a comprehensive framework on the different human cognitive processes (i.e., the "what") while classifying such processes into two key categories: the "Perception" and the "Response". Each of these process categories are translated to multiple traits, which researchers have attempted to incorporate into existing modeling framework with different levels of successes. In particular, within the perception category, the following traits were studied: the reaction time (*33*, *164*, *165*), the estimation errors (*164*, *166–170*), the perception thresholds (*171*, *172*), anticipation in space and time (*127*, *164*, *170*, *173*, *174*) and distractions (*175–184*). Within the response category, the following traits have been tackled: the sensitivity to the stimuli (*171*, *172*), the drivers' preferences (*80*, *173*), the context sensitivity (*124*, *173*, *185*), the insensitivity or inertia (*171*, *172*), and the risk-taking tendencies (*124*, *162*, *186–189*).

Next we will turn to a discussion of the recent shifts in paradigms of TFT.

## NEW PARADIGMS OF TRAFFIC FLOW

Two major shifts in TFT research paradigms were made during the last few decades: one in the scale of traffic modelling and management and one considering emerging technologies (ITS, autonomous vehicles).

**Network-wide Models of Urban Traffic**
The first major paradigm shift in the TFT community was a change in the spatial scale at which surface transportation systems are modeled. Previously mentioned methods focused on behavior at specific locations, links or intersections, but recent work has modeled the collective behavior of vehicles over spatially compact urban regions and used this information to study aggregate traffic network dynamics. Initial efforts at this network-wide paradigm began in the 1960's and 1970's (*190–194*), but were limited by lack of available traffic data at the network-wide scale, which precluded the development of models that could model traffic network dynamics. One notable effort is Herman and Prigogine's two-fluid model, which related fraction of vehicles stopping with average vehicle speed and could be calibrated using data from a handful of probe vehicles traveling in the traffic stream (*18*, *195*, *196*). More recently, network-wide relationships between network production (measured in average vehicle flow or rate that trips could be completed) and network accumulation (number of vehicles traveling or average vehicle density) were examined using first simulation (*197*, *198*) and eventually, empirical data (*199*, *200*). These relationships are known as Network or Macroscopic Fundamental Diagrams (N/MFDs). Daganzo and Geroliminis (*201*)

proposed the 'cuts method' based on the variational theory to analytically derive the MFD for an urban corridor, which was further improved in (*202*). Daganzo (*203*) showed how networks MFDs could be used to model traffic network evolution and identify basic control strategies to improve overall network efficiency. MFD-based regional modeling frameworks have been used to develop various large-scale control strategies to improve network efficiency by minimizing total vehicle travel time and mitigating congestion. These control strategies include: perimeter flow control (otherwise known as metering or gating), which identifies rates that vehicles should be allowed to move between regions of a network to improve network efficiency (*198*, *203–210*) (*209–216*); area-wide congestion pricing (*217–220*); allocation of space between various modes in a network (*221*, *222*); and, the use of one-way and two-way streets in urban regions (*223–226*). Other studies have focused on the properties of these network-wide relationships, including network instabilities, multivaluedness and hysteresis, and strategies to mitigate these to produce more reliable and well-defined relationships (*227–238*), and the development of new functional forms (*238–240*).

Some of the early studies on network-wide traffic also accounted for the interactions between cars and transit (*241*, *242*), evaluating not only the space consumed by each mode, but also their travel times. Smeed (*243*) estimated the average travel time for different cities depending on the modal split, showing that dependance on private cars was relatively fine for small towns, but could lead to significant delays for cities with 100,000 commuters or more. Owen (*244*) highlighted the need for better public transport solutions while simultaneously curbing the widespread use of the private car through some innovative traffic management strategies (e.g. car-free locations, congestion pricing). This idea was further reinforced with the Downs-Thomson paradox – the notion that to improve average travel speeds in cities it is imperative to improve the operations of public transport (*245*, *246*). Most recently, the MFD has been extended to capture the performance of multiple modes across the network (*247*) using a 3D-MFD version (*248*, *249*), and a number of efforts have been made to model multi-modal settings using either a similar concept (*250–253*) or higher order models (*254*).

**Traffic Flow Modeling for Emerging Technologies**
With the emergence of connected as well as connected and automated vehicle (CAV) technologies, a need to model such vehicles has arisen for simulation purposes. While connected vehicles convey information between vehicles, infrastructure, and road users using wireless technology, automated vehicles may operate without direct input from the driver (*255*). Although some automation technologies do not rely on connectivity, the higher levels of automation will likely require connectivity to reach the most ideal outcomes (*255*). Currently, two types of microscopic traffic modeling account for CAVs: logic-based models and vehicle dynamics/mechanistic models.

In theory, most existing car-following models could be considered logic-based traffic flow models with their generated traffic being considered automated. Several recent studies analyzed traffic flow properties using logic-based models with varying percentages of automated and/or connected vehicles (*256–260*). As highlighted in (*261*), most existing studies show that significant improvements can be achieved in most traffic flow performance measures as well as traffic string stability. Major drawbacks come from the use of simulation-based analyses and the lack of data needed to calibrate parameters for CAVs, as well as human driver behavior/attitudes toward the emerging. More recent work involves developing analytical frameworks to gain insight into the effects of CAVs on traffic flow (*262*, *263*).

Vehicle dynamics/mechanistic models focus on the vehicular aspects such as the steering, brake system and throttle, aerodynamics, rolling resistance, and even emissions and how they are modeled for connected and automated capabilities. Much of the focus of the latest research is on the control systems of the equipped vehicles in various platoon sizes (*69*, *264*, *265*). Traffic metrics of interest include not only string stability, but also internal stability for assessing controller design and effectiveness (*69*). An optimal control model for the mechanistic aspects of fuel consumption and emissions for CAVs has been developed for an intersection setting (*266*). Although these models capture detailed mechanistic features, they typically assume homogeneity in the type of CAV technology, and the human behavior/interaction with the systems is not prioritized.


## FUTURE DIRECTIONS

There are many challenges for future developments in the field of TFT. The TFTC Committee should consider ways to become a clearinghouse for understanding traffic flow phenomena at multiple scales based on solid empirical studies, to be a forum for debate and discussions of conflicting evidence, and to serve as a repository for empirical data. In the last years, we observed an acceleration of the introduction of new technologies and services in transportation system. This is an invigorating stimulus for the TFTC committee towards revisiting the fundamentals of TFT and develop improved and further integrated simulation tools. Outlined below are four primary arenas where there are opportunities for major investments in research and improved systems.

**Simulation**
There are many challenges for improved simulation tools that should be addressed. There is a need for improved realism of driving behavior models—particularly in congested and oversaturated traffic conditions. There has been increased interest in the prediction of traffic safety and environmental impacts based on simulation models. There is also a need for the models and tools to encompass the full range of modes (including freight transit, bicycling and walking) and to account for the interaction of these modes. Multi-resolution modeling and real-time modeling of traffic flow are also important topics of research and development. The collection of trajectory data is becoming more feasible and methods for collecting this type of data and its use in the calibration and validation are needed.

Several efforts are underway to simulate the operation and analyze scenarios for emerging transportation systems and services. Most notably CAVs create many uncertainties that simulation tools need to model. Issues include modeling CAVs interactions with other vehicles (human-driven vehicles) and non-motorized modes (e.g., pedestrians and bicycles), measurement errors from the various sensors employed under different infrastructure conditions, the effect of false positives and false negatives of object detection and position have on these CAVs, and how temporal and spatial infrastructure changes influence the efficiency and effectiveness of these CAVs.

Utilizing simulation modeling as part of decision support systems to improve transportation system performance in real-time environment introduces additional challenges. Running simulation models should have low latency such that the prediction of the performance and impacts can be done in a timely manner. In addition, calibration of these models based on real-time data, possibly

coming from CAVs in part, will improve the prediction capabilities of these models. Consideration should be given to the development of nanoscopic traffic flow models by incorporating engine performance, vehicle dynamics, intelligent drivers, and vehicle movement on a true two dimensional surface. Driving forces come from the need for more fidelity in safety, emissions, automatic cruise control, potential automated highway vehicle systems, etc.

**Connectivity and Automation**

Some of the most visible CAV leaders are currently private companies that have operated CAVs on public roads. While the feat is impressive, the implications for the TFT community are limited due to the private nature of the collected data. The USDOT Intelligent Transportation Systems (ITS) Joint Program Office (JPO) provides the opportunity to researchers to gain access to any of their seven test beds around the U.S. through a series of outlined steps (*267*). However, these testbeds are for connected vehicles and do not include any level of automation. Additionally, the USDOT ITS JPO created an online public database for researchers to upload and share ITS data and research findings (*268*). Even with these resources, there is still no standard for collecting data to be utilized by the traffic flow community.

Much work is being conducted to improve the traffic flow community's understanding of connected and automated vehicle impact on our roadways. Aspects of the logic-based and vehicle dynamics/mechanistic traffic flow models as well as models that attempt to capture human behavior in these changing roadway environments should be combined. Notably, although CAV models are mainly employed to remove human errors, their performance will depend on the way the humans/customers use the system. Thus, modeling the performance of CAVs will necessitate modeling the human factors interacting and operating such CAVs. Furthermore, with this integration comes the even greater need of data for both the driving logics as well as the mechanistic components. With this integration and access to data for calibration, the collective effects of emerging technologies on overall traffic could be analyzed.

Two data collection methods are the use of virtual environments or driving simulators and the use of instruments vehicles on testbeds/public roads. Driving simulators allow for a broad range of applications to be tested safely in a virtual environment (*269–272*). While much can be learned from driving simulator studies, the virtual aspect of driving simulators can be a downside. This leads to the implementation of instrumented vehicles, which are equipped with various sensors (e.g. LiDAR and RADAR), cameras, GPS, and control systems to obtain fine scope data regarding trajectories, headways, surrounding traffic, vehicle performance, subject reaction times, and subject attitudes. Some of these vehicles are used for data collection and automated vehicle research (*82, 123, 269, 270, 273–275*). Others are being used for connected and automated vehicle research (*269, 270, 276*).

**Network-level or Regional Urban Traffic Control**

The existence of well-defined network MFDs allows large-urban networks to be abstracted into a handful of regions and provides a computationally efficient way to model regional congestion dynamics. This paves the way to multiple applications. First, much work remains to improve large-scale MFD-based control strategies, such as perimeter control, optimal routing, pricing and others. In particular, how these regional control actions can be coordinated with local controllers (e.g. individual traffic signals) is very important to ensure the overall system efficiency. Second, field

implementation for the control strategies and thorough validation for the models are crucial as a large body of the literature still resorts to idealized test cases and simulated networks. Third, the impacts of autonomous and/or connected vehicles and new mobility service on MFD properties and system dynamics are open areas of research. It would be interesting to investigate how MFD models can be used as a new tool for urban planning and land-use studies. Finally, network-wide traffic models are needed to estimate a variety of metrics, such as safety and environmental impacts. Preliminary work has been performed on the former (*277*).

**Multi-modal Transportation Systems**
The existence of clear macroscopic relations between buses and cars, is now prompting new research extending to other modes, including bicycles and pedestrians (*247*). These models not only lead to a better understanding of the interactions across modes, but can contribute to innovative strategies that look at the system holistically, and aim to improve overall people mobility. This is more relevant each day as the distinction between modes is slowly disappearing with the concept of shared economies (*278*, *279*); an idea that is expected to evolve much further with automated vehicle technologies (*280*). New technologies, in general, are contributing to more flexible transport services, including concepts such as mobility as a service (MaaS) and mobility on demand (MOD) (*281*). The goal of many of these new transport alternatives is to better tailor the provided solutions to the real time changes in demand.

## ACCOMPLISHMENTS AND GOALS OF TFTC COMMITTEE

Over the years, the TFTC committee has authored two important documents, Monograph on Traffic Flow Theory and Transportation Systems Simulation Manual (TSSM), as described above. Since publication, the monograph has been used widely not only for research but also for education and a guide for young scholars. It is anticipated that the TSSM will have similar impacts but also reach out to practitioners that use simulations for their analyses and decision making. The TFTC committee has also authored "TRB E-Circular 197: Celebrating 50 Years of Traffic Flow Theory" involving the presentations at the TFTC summer meeting on August 11–13, 2014 in Portland, Oregon. The publication reflects on the traffic flow related research in the past 50 years and provides a glimpse of future research directions.

The TFTC committee has also formed three official subcommittees based on active research areas:
- AHB45(1) Joint Subcommittee on Simulation ("SimSub")
- AHB45(2) Crowd Flow Dynamics, Modeling and Management Subcommittee ("CrowdSub")
- AHB45(3) Traffic Flow Modeling for Connected and Automated Vehicles ("CATSub")

These subcommittees lead various important activities for the community including organizing workshops at TRB, issuing call for papers in strategic topics (for Annual meetings of TRB and other journals), representing the committee at various conferences, etc. AHB45(1) SimSub was created in 2005, in cooperation with seven other TRB committees: Transportation Network Modeling (ADB30), Freeway Operations (AHB20), Traffic Signal Systems (AHB25), Highway Capacity and Quality of Service (HCQS) (AHB40), Work Zone Traffic Control (AHB55), Managed Lanes Committee (AHB35), and Transportation and Air Quality (ADC20). SimSub

coordinates the efforts of its eight parent committees to promote and endorse the use of simulation tools in transportation system analysis. SimSub is working closely with the TFTC committee and the TSSM development team to develop research problem statements and to support the provision of guidelines for the analysis, modeling, and simulation (AMS) of emerging technologies.

The Crowd Dynamic Subcommittee is part of TFTC committee and is supported by the Emergency Evacuation Committee (ANB80). The subcommittee promotes research in the area of empirical analyses, modeling, simulation, and management of crowds. Since established in 2014 the subcommittee organized two workshops and sponsored call for papers in every TRB annual meetings. The members of the subcommittee are involved in other well-known crowd dynamics international scientific committees including TFG and PED.

Anticipating transformative impacts of the CAV technology, the TFTC committee has formed AHB45(3) CATSub in 2014. Since its creation, the subcommittee has organized several workshops at TRB and sessions at the Autonomous Vehicles Symposiums (AVS). The summary of the presentations and the recommendations made by the organizers and panel members resulted in three book chapters (*282–284*).

The TFTC committee has also engaged in a variety of activities through unofficial subcommittees. After the successful Greenshields 75 Symposium in 2008, the TFTC committee established the Greenshields Prize, named in honor of Dr. Bruce D. Greenshields, a pioneer in our field. The Greenshields Prize recognizes annually a high-quality paper founded on real data analysis. A new award for the best theoretical contribution was established in 2018. The Awards subcommittee also provides nominations for other TRB awards including the Mickle and Burggraf awards (TRB-wide) and the Cunard award (Operations section-wide). The TFTC committee is proud to count two Mickle's awards (2016 and 2017), one Burggraf's award (2017) and six Cunard awards.

The Outreach and Diversity subcommittee has engaged in a variety of outreach activities through committee newsletters, website, Facebook, and Twiter. The subcommittee also hosted 68 webinars from 2010 to 2016. Through various subcommittee and outreach activities, the TFTC committee has engaged in young and diverse scholars. In recognition, the TFTC committee was awarded a Blue Ribbon Award in 2015 in the category of "Community Building & Mentoring: Committee on Traffic Flow Theory and Characteristics for engaging young diverse participants through innovative and inclusive outreach; and collaboration in research, education and training."

The TFTC committee has been a hub for traffic flow researchers to share knowledge, inspire new research directions, and welcome emerging scholars since its birth. The committee will continue this tradition and serve as a main venue for traffic flow researchers, where diverse ideas, approaches, members, and friends are welcome regardless of the school of thoughts, affiliation, race, gender, stage of career, etc. By nature, the TFTC committee is inclined for more fundamental research of traffic flow. However, the committee recognizes the importance of connection from research to practice and will continue to seek and engage government agencies as well as private industry. This is particularly important in the era of the fast-developing CAV technologies, where partnerships among different sectors are essential.

Historically, the TFTC committee has been close to several other committees and partnered with them for a variety of activities such as calls for papers, midyear meetings, workshops, etc. The committee will continue to partner with other committees, including:

- AHB15 Standing Committee on Intelligent Transportation Systems
- AHB20 Standing Committee on Freeway Operations
- AHB25 Standing Committee on Traffic Signal Systems
- AHB30 Standing Committee on Vehicle-Highway Automation
- AHB40 Standing Committee on Highway Capacity and Quality of Service
- ADB30 Standing Committee on Transportation Network Modeling

It is expected that as the field develops, the committee will adapt, lead new activities, and seek out new partnerships.

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