Guest Editorial
Introduction to the Special Issue on Intelligent Transportation Systems Empowered by AI Technologies

THERE has been an increasing level of demand for faster, safer and greener transportation systems with higher levels of capacity and convenience, though the implementation of transportation systems overall is often restricted by geographical limitations, presenting a challenge to scientists and engineers in the field. However, we have been witnessing the evolution of the transportation systems over the last few decades, and at present we are facing a new era of intelligent transportation systems (ITS) empowered by artificial intelligence (AI) technologies. There have been classification, deep learning, and reinforcement learning techniques, to name a few, which collectively have enabled almost all technical elements of the ITS. For example, autonomous vehicle technologies are now mature enough to introduce self-driving cars, taxis, buses, and trucks on the roads and streets; traffic signals are controlled by AI-based systems for far more enhanced traffic efficiency; and machine learning based on big data is improving the operational performance of transportation systems to the next level of safety, efficiency, and sustainability.

This Special Issue aims to take the opportunity to introduce current developments, the progress, and the advancements of not only the technical elements of the ITS empowered by the AI technologies but also the innovative AI techniques combined with the domain knowledge of transportation and mobility systems, from both theoretical and practical perspectives. This special issue of IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS can be a flagship issue to draw the attention of the technical and scientific communities to the AI technologies studied and applied in relation to the new generation of ITS. In detail, the scope of the special issue ranges from the innovative AI techniques in the ITS to the advanced ITS with AI technologies in the following fields (but not limited to these fields):

- New transportation, mobility, and logistics systems
- Impact of AI technologies on intelligent transportation systems
- Traffic modeling, prediction, management, and control
- Enhanced security and safety in transportation systems
- Innovative localization and navigation technologies
- V2X communication systems and their applications

- Human-machine interaction including human behaviors in intelligent vehicles
- Autonomous, connected, and cooperative driving systems
- Advanced driver-assistance systems and their impact on transportation
- Sensors and sensing technologies
- Intelligent infrastructure for transportation systems
- Surveillance and monitoring technologies for transportation

Our call for papers received an extensive response with 44 high quality submissions relevant to the theme of our Special Issue from all over the world. In the review process, it was ensured per IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS policy that Guest Editors had no potential conflict of interest with the authors of the submitted articles being handled. The submitted articles were evaluated for their novelty, significance, contribution, and overall quality required by IEEE journals. As a result, we accepted 17 articles that received positive recommendations from at least three independent reviewers.

The accepted 17 articles introduce topics in a wide range of advanced ITS techniques using AI. The first seven articles introduce studies of AI techniques for intelligent vehicle, and the next seven articles talk about AI techniques for traffic and trajectory prediction problems. The last three articles introduce studies using AI techniques for other various problems in ITS, such as transit network design, prediction of pedestrian walking behavior, and representing locations in a vectorized form for situation-awareness.

Special Issue Short Summaries

Logistical Planning for Electric Vehicles Under Time-dependent Stochastic Traffic

X. Bi and W. K. S. Tang

The technical problem of limited drivable range and long charging duration has been the major hurdle for the popularization of electric vehicles (EVs), especially for commercial usage. This paper proposes a dynamic electric vehicle routing problem (D-EVRP) model to plan the itinerary for goods delivery with the utilization of EVs in logistics industry. D-EVRP considers a time-dependent stochastic traffic condition and captures the discharging/charging pattern of EV using an analytical battery model. Its aim is to minimize the overall

service duration, subject to a variety of state-of-art constraints common in EV routing problems. To address the D-EVRP, a hybrid rollout algorithm (HRA), incorporating a dedicated pre-planning strategy and a rollout algorithm, is proposed. Its effectiveness, together with the benefits of analytical battery modeling, are justified by extensive simulations using real-world D-EVRP instances.

A Survey on 3D Object Detection Methods for Autonomous Driving Applications

E. Arnold, O. Y. Al-Jarrah, M. Dianati, S. Fallah, D. Oxtoby, and A. Mouzakitis

An Autonomous Vehicle (AV) requires an accurate perception of its surrounding environment to operate reliably. The perception system of an AV transforms sensory data into semantic information that enables autonomous driving. Object detection is a fundamental function of this perception system. This paper presents an overview of 3D object detection methods and prevalently used sensors and datasets for such application in AVs. It then discusses and categorizes recent works based on sensor modalities. The results of the surveyed works are summarized and research gaps are identified along with future research directions.

Reinforcement-Learning-Based Cooperative Adaptive Cruise Control of Buses in the Lincoln Tunnel Corridor With Time-Varying Topology

W. Gao, J. Gao, K. Ozbay, and Z.-P. Jiang

A novel data-driven cooperative adaptive cruise control (CACC) algorithm is proposed for connected and autonomous buses along the exclusive bus lane of the Lincoln Tunnel approach corridor. Different from existing model-based CACC algorithms, the proposed approach employs the idea of reinforcement learning, which does not rely on accurate knowledge of bus dynamics. Considering a time-varying topology where each autonomous vehicle can only receive information from vehicles that are within its communication range, a distributed controller is learned in real-time by online headway, velocity, and acceleration data collected from system trajectories. Simulation results show that the travel times in the autonomous version of the exclusive bus lane are close to the present day travel times even when the bus volume is increased by 30%.

Online Vehicle Routing With Neural Combinatorial Optimization and Deep Reinforcement Learning

J. J. Q. Yu, W. Yu, and J. Gu

Online vehicle routing is an important task of modern transportation service provider. Existing routing algorithms are mostly based on mathematical programming, which requires huge computation time in city-size transportation networks. To develop routes with minimal time, in this work we propose a novel deep reinforcement learning-based neural combinatorial optimization strategy. Specifically, we transform the online routing problem to a vehicle tour generation problem, and propose a structural graph embedded pointer network to develop these tours iteratively. Furthermore, since constructing supervised training data for the neural network is imprac-

tical due to the high computation complexity, we propose a deep reinforcement learning mechanism with an unsupervised auxiliary network to train the model parameters. A multisampling scheme is also devised to further improve the system performance. Since the parameter training process is offline, the proposed strategy can achieve a superior online route generation speed.

Driver Pose Estimation Using Recurrent Lightweight Network and Virtual Data Augmented Transfer Learning

Y. Liu, P. Lasang, S. Pranata, S. Shen, and W. Zhang

Driver poses recognition is of paramount interest for the advanced driver assistance systems (ADAS). Recently proposed methods intend to use deeper and more complicated networks to achieve better performance, which leads to heavy models that are not feasible for the resource limited applications. To resolve this issue, we have worked on the following aspects. 1) a lightweight network model, which is referred to as recurrent multi-task thin net (RM-ThinNet), has been proposed which was especially designed for the computationally and memory limited devices. 2) a recurrent structure has been introduced to handle the scale difference and dependency between different tasks, and this recurrence ensures the different tasks are accomplished at different stages and their outputs can augment each other. 3) A virtual data synthetization pipeline and a couple transfer learning method have been presented, by which network can be learnt effectively by relatively small number of real data.

Predictive Cruise Control Using Radial Basis Function Network-Based Vehicle Motion Prediction and Chance Constrained Model Predictive Control

S. Yoon, H. Jeon, and D. Kum

Radial base function network (RBFN) based probabilistic motion prediction algorithm is proposed which can accurately compute the likelihood of multiple target lanes and trajectories of surrounding vehicles. In addition, Chance-constrained model predictive control (CCMPC) is utilized in order to apply RBFN based future prediction into predictive cruise control (PCC) problem, because the chance constraints in CCMPC can handle collision uncertainties associated with future uncertainties. Simulation results show that the RBFN-based CCMPC achieves higher collision avoidance success rate than that of the IMM-based CCMPC while using smaller actuator inputs and providing higher passenger comforts. Furthermore, the RBFN-based CCMPC also showed high robustness to false braking during near lane-change (lane-keeping) scenarios.

An Unsupervised Cluster-Based VANET-Oriented Evolving Graph (CVoEG) Model and Associated Reliable Routing Scheme

Z. Khan, P. Fan, S. Fang, and F. Abbas

In vehicular ad-hoc networks (VANETs), communication links break more frequently due to the high-speed vehicles. Cluster-based VANET oriented Evolving Graph (CVoEG) model is proposed by extending the existing VoEG model to improve the reliability of vehicular communications. The link reliability is used as a criterion for cluster members (CMs)

and cluster heads (CHs) selection. The proposed CVoEG model divides VANET nodes (vehicles) into an optimal number of clusters (ONC) by using eigengap heuristic. In a given cluster, a vehicle will be selected as a CH, if it has a maximum eigen-centrality score. Based on the CVoEG model, a cluster based evolving graph reliable ad-hoc on demand distance vector (CEG-RAODV) routing scheme is proposed to find the most reliable journey from source to destination.

A Scalable Framework for Trajectory Prediction

P. Rathore, D. Kumar, S. Rajasegarar, M. Palaniswami, and J. C. Bezdek

This paper presents a smart city application of big data clustering for intelligent transportation systems. Specifically, a scalable framework, based on big data clustering and Markov models, is developed for vehicle trajectory prediction which is suitable for a large number of overlapping trajectories in a dense road network, typical for major cities around the world. The short-term and long-term prediction performance of proposed framework on two real-life, large-scale taxi trajectory data from the Beijing and Singapore Road networks is found to be better than baseline approaches in terms of prediction accuracy and distance error.

Contextualized Spatial–Temporal Network for Taxi Origin-Destination Demand Prediction

L. Liu, Z. Qiu, G. Li, Q. Wang, W. Ouyang, and L. Lin

The task of existing taxi demand prediction is extended to more challenging and worth exploring task called taxi origin-destination demand prediction, which aims at predicting the taxi demand between all region pairs in a future time interval. A novel Contextualized Spatial-Temporal Network is proposed to address this problem. This method integrates the local spatial context, temporal evolution context and global correlation context into a unified framework. Appropriate neural networks were separately designed to exploit above three contexts effectively for taxi original-destination demand prediction. Extensive experiments on a large-scale benchmark demonstrate that the proposed method outperforms existing state-of-the-art methods by a margin.

Taxi-Based Mobility Demand Formulation and Prediction Using Conditional Generative Adversarial Network-Driven Learning Approaches

H. Yu, X. Chen, Z. Li, G. Zhang, P. Liu, J. Yang, and Y. Yang

A deep learning framework, including a modified density based spatial clustering algorithm with noise (DBSCAN) and a conditional generative adversarial network (CGAN), is proposed to predict the taxi-passenger demand. The modified DBSCAN is applied to produce a number of sub-networks considering the spatial correlation of taxi-passenger demand in road network. The CGAN model, fed with the historical taxi-passenger demand and other conditional information, is capable to predict the taxi-passenger demands with long short-term memory (LSTM) technique. The spatial, the temporal, and external dependencies are thus considered simulta-

neously. The predictive performance of the proposed approach is demonstrated based on numerical experimental results.

A Multi-Objective Agent-Based Control Approach With Application in Intelligent Traffic Signal System

J. Jin and X. Ma

This paper presents a multi-agent framework that models traffic control instruments and their interactions with road traffic in the context of multi-objective policy goals. A reinforcement learning-based computational framework is developed for control applications. The agent decision making is represented by a constrained Markov decision process (CMDP) model. To implement the multi-objective decision model, a threshold lexicographic ordering method is introduced and integrated with the learning-based algorithm. Moreover, a two-stage hybrid framework is established to improve the learning efficiency of the model. The computational results show that the proposed control approach can handle a complex case of multiple policy requirements. Meanwhile, the agent-based intelligent control has shown superior performance when compared to other optimized signal control methods.

Deep Spatial–Temporal 3D Convolutional Neural Networks for Traffic Data Forecasting

S. Guo, Y. Lin, S. Li, Z. Chen, and H. Wan

A novel end-to-end deep learning model, called ST-3DNet, is proposed for traffic raster data prediction. ST-3DNet introduces three-dimensional (3D) convolutions to automatically capture the correlations of traffic data in both spatial and temporal dimensions. And a novel "Recalibration" (Rc) block is proposed to explicitly quantify the difference of the contributions of the correlations in space. Considering two kinds of temporal properties of traffic data, i.e., local patterns and long-term patterns, ST-3DNet employs two components consisting of 3D convolutions and Rc blocks to respectively model the two kinds of patterns and then aggregates them together in a weighted way for the finial prediction. Experimental results demonstrate that our ST-3DNet outperforms the state-of-the-art baselines

Deep and Embedded Learning Approach for Traffic Flow Prediction in Urban Informatics

Z. Zheng, Y. Yang, J. Liu, H.-N. Dai, and Y. Zhang

In this paper, we propose a Deep and Embedded Learning Approach (DELA) that can explicitly learn from fine-grained traffic information, route structure, and weather conditions. In particular, our DELA consists of an embedded component, a Convolutional Neural Networks (CNN) component, and a Long Short-term Memory (LSTM) component. The embedded component can capture the categorical feature information and identify correlated features. Meanwhile, the CNN component can learn the 2-Dimensional (2-D) traffic flow data while the LSTM component has the benefits of maintaining a long-term memory of historical data. The integration of the three models together can improve the prediction accuracy of traffic flow. We conduct extensive experiments on realistic traffic flow dataset to evaluate the performance of our DELA and make

comparison with other existing models. The experimental results show that the proposed DELA outperforms existing methods in terms of prediction accuracy.

Real-Time Traffic Speed Estimation With Graph Convolutional Generative Autoencoder

J. J. Q. Yu and J. Gu

Real-time traffic speed estimation is an essential component of intelligent transportation system technologies. It is the foundation of modern transportation control and management applications. However, existing traffic speed acquisition systems can only provide real-time speed measurements of a small number of roads with stationary speed sensors and crowdsourcing vehicles. How to utilize this information to provide traffic speed maps for transportation networks is becoming a key problem in intelligent transportation systems. In this work, we present a novel deep learning model called graph convolutional generative autoencoder to fully address the real-time traffic speed estimation problem. The proposed model incorporates the recent development of deep learning techniques to extract the spatial correlation of the transportation network from the input incomplete historical data. The simulation results demonstrate that the proposed technique can notably outperform existing traffic speed estimation and deep learning techniques.

Solving Transit Network Design Problem Using Many-Objective Evolutionary Approach

M. A. Nayeem, M. M. Islam, and X. Yao

In a modern city, the transit network (i.e., public bus network) involves different stakeholders (e.g. passenger, bus operator, local authority, etc.) with diverse interests and values. A practical, green and economical transit network must capture their conflicting expectations in the best possible way. To design such a network, it is necessary to deal with many interdependent objectives at the initial stage of planning. Traditional approaches combine several objectives into one. However, it requires extensive domain knowledge that may not be available at the initial stage. On the contrary, this paper proposes a many-objective evolutionary approach which optimizes each objective independently. The simulation results show that, by allowing generate a diverse set of alternative solutions, the proposed approach gives transport planners a comprehensive understanding of the situation and provides a greater flexibility to select the solution that best matches their requirements.

An Intelligence-Based Approach for Prediction of Microscopic Pedestrian Walking Behaviour

Y. Ma, E. W. Lee, Z. Hu, M. Shi, and R. K. Yuen

This paper proposes an intelligent behavioral learning approach to predict microscopic pedestrian walking behavior within natural footstep duration. In the proposed approach, a pedestrian's motion behavior is governed by a special neural network that incorporated real human knowledge and experience. The approach can capture the underlying decision-making mechanism behind pedestrian walking behavior, and predict the speed, direction and position adjustment behavior of an individual pedestrian at each step in terms of the perceived environmental information including destination, obstacles, and neighbors. In addition, the extended application also shows that the proposed approach has promise for simulation of the short-term flow of a pedestrian crowd.

Location2vec: A Situation-Aware Representation for Visual Exploration of Urban Locations

M. Zhu, W. Chen, J. Xia, Y. Ma, Y. Zhang, Y. Luo, Z. Huang, and L. Liu

Understanding the relationship between urban locations is an essential task in urban planning and transportation management. We design a spatial embedding algorithm to encode urban locations with a vectorized representation while retaining the mutual influence between urban locations and mobility behavior. To explore our proposed technique, we have designed and implemented a web-based visual exploration system that supports the comprehensive analysis of human mobility, location functionality, and traffic assessment by leveraging the proposed visual representation.

SEUNG-HYUN KONG, *Guest Editor*
Korea Advanced Institute of Science
and Technology (KAIST)
Daejeon 34141, South Korea
e-mail: skong@kaist.ac.kr

YISHENG LV, *Guest Editor*
Institute of Automation,
Chinese Academy of Sciences
Beijing 100190, China
e-mail: yisheng.lv@ia.ac.cn

HAI L. VU, *Guest Editor*
Monash University
Melbourne, VIC 3800, Australia
e-mail: hai.vu@monash.edu

JUAN-CARLOS CANO, *Guest Editor*
Universitat Politecnica de Valencia
46022 Valencia, Spain
e-mail: jucano@disca.upv.es

BRENDAN TRAN MORRIS, *Guest Editor*
University of Nevada
Las Vegas, NV 89154 USA
e-mail: brendan.morris@unlv.edu

JUN-WON CHOI, *Guest Editor*
Hanyang University
Seoul 04763, South Korea
e-mail: junwchoi@hanyang.ac.kr

DONGSUK KUM, *Guest Editor*
Korea Advanced Institute of Science
and Technology (KAIST)
Daejeon 34141, South Korea
e-mail: dskum@kaist.ac.kr

Seung-Hyun Kong (SM'16) received the B.S. degree in electronics engineering from Sogang University, Seoul, in 1992, the M.S. degree in electrical and computer engineering from Polytechnic University, New York, in 1994, and the Ph.D. degree in aeronautics and astronautics from Stanford University, Palo Alto, in 2005. He has more than 12 years of research and development experience in the industry, including with Samsung Electronics, South Korea, and Qualcomm, San Diego, USA, where he was involved in mobile communication systems, wireless positioning, and assisted GNSS. He is currently an Associate Professor with The CCS Graduate School of Green Transportation, Korea Advanced Institute of Science and Technology (KAIST), South Korea, where he has been a Faculty Member since 2010. He has authored or coauthored more than 100 refereed journal articles and conference articles and invented or co-invented 15 patents. His research interests include machine learning for vehicular localization and navigation systems, connected autonomous vehicle systems, GNSS signal processing, and deep learning techniques for sensors and sensor fusion. He has served as a Lead Guest Editor for a special section of the IEEE ACCESS on GNSS, localization, and navigation technologies, and for a Special Issue of the IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS on ITS empowered by AI technologies. He is currently an Editor of *IET Radar, Sonar and Navigation* and an Associate Editor of the IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS and IEEE ACCESS.

Yisheng Lv received the B.E. and M.E. degrees from the Harbin Institute of Technology in 2005 and 2007, respectively, and the Ph.D. degree from the Chinese Academy of Sciences, Beijing, China, in 2010. He is currently an Associate Professor with the State Key Laboratory of Management and Control for Complex Systems, Institute of Automation, Chinese Academy of Sciences. He is also with the Qingdao Academy of Intelligent Industries. His research interests include traffic data analysis, deep learning, machine learning, and parallel traffic management and control systems.

Hai L. Vu received the B.Sc./M.Sc. and Ph.D. degrees in electrical engineering from the Technical University of Budapest, Hungary, in 1994 and 1999, respectively.

After five years at The University of Melbourne and 11 years at the Swinburne University of Technology, he joined the Engineering Faculty, Monash University, Melbourne, Australia, in 2016, where he is currently a Professor and leads intelligent transport systems (ITS) research in the Civil Engineering Department. He has authored or coauthored over 180 scientific journals and conference articles. His research interests include the modeling, performance analysis, and design of complex networks and stochastic optimization and control with applications to connected autonomous vehicles and intelligent transportation. He was a recipient of prestigious research awards in 2012, the Australian Research Council (ARC) Future Fellowship and the Victoria Fellowship Award for his research in ITS. More information can be found at https://www.monash.edu/engineering/lehaivu.

Juan-Carlos Cano received the M.Sc. and Ph.D. degrees in computer science from the Polytechnic University of Valencia (UPV), Spain, in 1994 and 2002, respectively.

From 1995 to 1997, he was a Programming Analyst with the Manufacturing Division, IBM, Valencia. He is currently a Full Professor with the Department of Computer Engineering, UPV. He has published more than 250 conference and journal articles dealing with wireless networks. The most relevant publications are 70 journal articles in the JCR Science Edition of Thomson-ISI (15 of which are in the IEEE TRANSACTION series). His current research interests include wireless communications, vehicular networks, mobile ad hoc networks, and pervasive computing. He has an H factor of 35. Concerning his professional activities in intelligent transport systems (ITS), he has been the General Chair of the Wireless Days Conference 2013, Tutorial Co-Chair of the 12th ACM MSWIM Conference, General Chair of the 4th and 5th ACM Workshop PM2HW2N, Publicity Chair of the 2nd IEEE Intelligent Vehicular Communications Workshop of 2010, and TPC Vice-Chair of the 3rd IEEE Vehicular Networks & Applications Workshop. In January 2010, he was elected the ITS Europe News Editor for the IEEE ITS Society Technical Committee on Mobile Communication Networks, and has served in the IEEE ITS Society since then. He is also a TPC member of several international conferences sponsored by the IEEE, ACM, and IFIP, and acts as a regular reviewer for journals and conferences. More info can be found at http://www.disca.upv.es/jucano/.

Brendan Tran Morris received the B.S. degree from the University of California at Berkeley, Berkeley, CA, USA, in 2002, and the Ph.D. degree from the University of California at San Diego, La Jolla, CA, USA, in 2010. He is currently an Associate Professor of electrical and computer engineering and the Founding Director of the Real-Time Intelligent Systems Laboratory, University of Nevada, Las Vegas, NV, USA. He and his team researched computationally efficient systems that utilize computer vision and machine intelligence for situational awareness and scene understanding. He serves as an Associate Editor for the *IEEE Intelligent Transportation Systems Magazine* and the IEEE ROBOTICS AND AUTOMATION LETTERS.

Jun-Won Choi received the B.S. and M.S. degrees from the Electrical Engineering Department, Seoul National University, and the Ph.D. degree in electrical computer engineering from the University of Illinois at Urbana–Champaign. In 2010, he joined Qualcomm, San Diego, USA, where he participated in research on advanced signal processing technology for next-generation wireless systems. Since 2013, he has been with the Electrical Engineering Department, Hanyang University, as a Faculty Member. His research area includes signal processing, machine learning, intelligent vehicles, and wireless communications. He has served as an Associate Editor for the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY and the IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS. He is a Reviewer for many technical journals, including the IEEE TRANSACTIONS ON SIGNAL PROCESSING and the IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS.
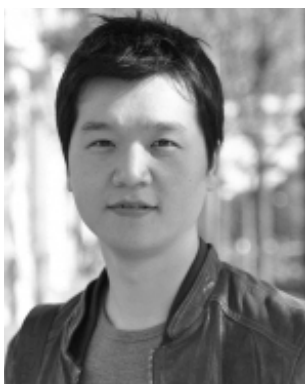
Dongsuk Kum received the Ph.D. degree in mechanical engineering from the University of Michigan, Ann Arbor, MI, USA, in 2010. He was with the General Motors R&D Propulsion Systems Research Laboratory, Warren, MI, USA, as a Visiting Research Scientist, where he was involved in advanced propulsion system technologies, including hybrid electric vehicles, flywheel hybrid, and waste heat recovery systems. He is currently an Associate Professor with the Graduate School of Green Transportation, Korea Advanced Institute of Science and Technology (KAIST), and the Director of the Vehicular System Design and Controls (VDC) Laboratory. His research centers on the modeling, control, and design of advanced vehicular systems, with particular interests in hybrid electric vehicles and autonomous vehicles.