様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

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研究課題名（和文）次世代交通システムに向けた階層化サイバーフィジカル制御の構築

研究課題名（英文）Next generation traffic control system using the cyber-physical framework

研究代表者
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交付決定額（研究期間全体）：（直接経費）　　3,300,000円

研究成果の概要（和文）：来るべきスマート交通システムに向けた車両交通制御策を新たに提案した。マルチエージェントシステムとみなされる異種車両を使用して道路交通を柔軟に最適化するためのサイバーフィジカルシステム制御の構造が提案された。その提案手法の有効性は、各交通シナリオで交通容量、流量、燃料消費量、排出ガスを改善するを確認された。

研究成果の学術的意義や社会的意義
The significances are the theoretical development of cyber-physical traffic control framework, receding horizon optimization of multi-agent systems, and efficient look-ahead driving schemes, besides the expected improvement in future transport sustainability with enhanced safety and comforts.

研究成果の概要（英文）：A cyber-physical traffic control framework is proposed to optimize network traffic flexibly with heterogeneous vehicles considered multi-agent systems. The system's effectiveness is evaluated in critical scenarios in improving traffic capacity, flows, fuel consumption, and emissions. The developed multi-agent-based traffic signal optimization schemes with a receding horizon approach can flexibly coordinate any vehicles, considered physical agents on the roads with their twin modeled in cyberspace, for smooth flows at the intersections. With multiple international collaborations, we extended the proposed cyber-physical framework beyond the intersection's traffic. Specifically, we consider all major traffic problem scenarios, e.g., a roundabout, mandatory overtaking cases, and merging scenarios. Moreover, the most significant development is the look-ahead driving schemes that improve other vehicles' performances and overall road capacity.

研究分野：Traffic and Transportation Control System

キーワード：Cyber-physical control　Connected vehicles　Optimal control　Cooperative Eco-driving

１．研究開始当初の背景

Conventional vehicular traffic systems cannot adequately control congestion, accidents, energy consumption, and exhaust gas emissions, burdening society. Injudicious driving (including aggressive acceleration/deceleration, risky speeding, and careless lane changes or merging), whether intentional or due to limitations in a human cognitive decision-making capacity, lead to excessive energy consumption and cause congestion and accidents. Recently developed automated vehicle driving technology allows a single vehicle to operate independently based on information on traffic conditions, engine characteristics, traffic lights, and road topography. Automated driving technologies with the existing conventional traffic system cannot eliminate traffic congestion to make traffic highly efficient. On the other side, the introduction of high-speed communication technology, smart devices, and automated vehicles is shifting the paradigm of road traffic systems. By using inter-vehicle communication and infrastructure communication, the entire traffic environment is linked, and each vehicle can obtain information on adjacent vehicles and the environment. The need for highly efficient and innovative road traffic control has emerged with upcoming technologies that ensure effective utilization of communication, cloud-edge computation, and automated vehicles to achieve highly efficient intelligent road transportation systems.

２．研究の目的

Considering the above background, the research objectives are set as follows: (1) Deriving a framework for cyber-physical control by using the edge-cloud computing method; (2) Developing adaptive traffic control methods for intersections, merging, and roundabouts; (3) Developing cooperative optimal vehicle control strategies; (3) develop an optimal cooperative vehicle control strategy; (4) verify the proposed method through urban traffic simulation using automated vehicles. The proposed cyber-physical control can be depicted as incorporating functional components, the cloud, road infrastructure, and vehicles with data fusion and optimization mechanisms. The ultimate goal is to improve overall traffic flows, energy consumption, and congestion.

３．研究の方法

The basic approach to the proposed traffic control system is to formulate a framework considering any vehicles and other objects (e.g., traffic lights) as physical agents while introducing one cyber-agent (i.e., digital twin) against each in the cloud by incorporating a realistic communication mechanism with cyber-centered computation technique, a practical cyber-physical framework is achieved. Such a framework is numerically implemented using computer programming by incorporating a traffic simulator. Adaptive signal control methods with flexible optimization techniques are developed by sorting out various decision processes needed for traffic control (e.g., traffic lights and merging signals) at intersections, merging, and roundabouts. Besides the cyber-based coordination, efficient vehicle control techniques using a model predictive controller are developed for cooperative driving. Finally, all these are evaluated using standard traffic simulators, and the outcomes are presented and published in international conferences and journals.

４．研究成果

Summary: A cyber-physical traffic control framework is proposed to optimize network traffic flexibly with heterogeneous vehicles considered multi-agent systems. The system's effectiveness is evaluated in critical scenarios in improving traffic capacity, flows, fuel consumption, and emissions. The developed multi-agent-based traffic signal optimization schemes with a receding horizon approach can flexibly coordinate any vehicles, considered physical agents on the roads with their twin modeled in cyberspace, for smooth flows at the intersections. With multiple international collaborations, we extended the proposed cyber-physical framework beyond the intersection's traffic. Specifically, we consider all major traffic problem scenarios, e.g., a roundabout, mandatory overtaking cases, and merging scenarios. Moreover, the most significant development is the look-ahead driving schemes that improve other vehicles' performances and overall road capacity.

Major achievements:

Control of Vehicular Traffic at an Intersection and Multi-lane Highways Using a Cyber-Physical Multiagent Framework

A novel cyber-physical multiagent framework was proposed to control traffic at an intersection. The vehicles, or physical agents, may pass the intersection smoothly utilizing the timings of traffic lights provided in advance. In the cyberspace, the durations of upcoming traffic lights are computed by a group of cyber agents using a stochastic gradient-based method known as broadcast control of multiagent systems. For this computation of the traffic light durations, a function that represents the cost for blocking a vehicle by the red light is included in the objective function, which is minimized by the cyber agents to collectively provide the least-restrictive right-of-way in a receding horizon control approach to all vehicles at the intersection.

> *Ref.: M. A. S. Kamal, C. P. Tan, T. Hayakawa, S. -I. Azuma and J. -I. Imura, "Control of Vehicular Traffic at an Intersection Using a Cyber-Physical Multiagent Framework," in IEEE Transactions on Industrial Informatics, vol. 17, no. 9, pp. 6230-6240, Sept. 2021.*

We presented a novel cyber-physical framework for optimal automated vehicles on multi-lane freeways to alleviate bottlenecks, considering all vehicles are connected to a cloud-based computing framework. In the proposed framework, the vehicles are coordinated into groups or platoons, and their trajectories are successively optimized in a receding horizon control (RHC) approach. Optimization of the traffic coordination system aims to provide sufficient gaps when a lane change is necessary while minimizing the speed deviation and acceleration of all vehicles. The coordination information is then provided to individual vehicles equipped with local controllers, and each vehicle decides its control acceleration to follow the target trajectories while ensuring a safe distance. Our proposed method guarantees fast optimization and can be used in real-time. The proposed coordination system was evaluated using microscopic traffic simulations and benchmarked with the traditional driving (human-based) system.

> *Ref.: Sakaguchi, Yuta, A. S. M. Bakibillah, M. A. S. Kamal, and Kou Yamada. "A Cyber-Physical Framework for Optimal Coordination of Connected and Automated Vehicles on Multi-Lane Freeways." Sensors 23, no. 2 (2023): 611.*

Traditional uncoordinated traffic flows in a roundabout can lead to severe traffic congestion, travel delay, and the increased fuel consumption of vehicles. An interesting way to mitigate this would be through cooperative control of connected and automated vehicles (CAVs). We proposed a novel roundabout control system (RCS), for CAVs to attain smooth and safe traffic flows. The RCS is essentially a bi-level framework, consisting of higher and lower levels of control, where in the higher level, vehicles in the entry lane approaching the roundabout will be made to form clusters based on traffic flow volume, and in the lower level, the vehicles' optimal sequences and roundabout merging times are calculated by solving a combinatorial optimization problem using a receding horizon control (RHC) approach. The proposed RCS aims to minimize the total time taken for all approaching vehicles to enter the roundabout, whilst minimally affecting the movement of circulating vehicles. Our developed strategy ensures fast optimization, and can be implemented in real-time.

> *Ref.: Bakibillah, A.S.M.; Kamal, M.A.S.; Tan, C.P.; Susilawati, S.; Hayakawa, T.; Imura, J.-i. Bi-Level Coordinated Merging of Connected and Automated Vehicles at Roundabouts. Sensors 2021, 21, 6533.*

Development of Driving Systems of Connected Automated Vehicles

Recently developed efficient driving schemes usually solve a predictive optimization problem at high computational cost. We presented a more practical technique for automated vehicles' predictive driving by extending the existing adaptive cruise control (ACC) scheme with a look-ahead functionality. Such a look-ahead driving scheme (LDS) predicts the states of the preceding vehicle at an adaptive look-ahead time step and, with negligible computation costs, computes the vehicle control input more circumspectly for efficient driving in urban traffic. The proposed LDS is evaluated in typical urban traffic at the signalized intersections by observing the intersection utilization, flowing characteristics, and individual vehicles' fuel efficiency. Furthermore, we also evaluate the influences of the LDS-vehicles' penetration rates on overall traffic performances at various traffic volumes.

> *Ref.: M. A. S. Kamal, K. Hashikura, T. Hayakawa, K. Yamada and J. Imura, "Look-Ahead Driving Schemes for Efficient Control of Automated Vehicles on Urban Roads," in IEEE Transactions on Vehicular Technology, vol. 71, no. 2, pp. 1280-1292, Feb. 2022.*

In the existing optimal driving, gravitational potential energy is not efficiently exploited and braking at down-slopes (which wastes energy) becomes unavoidable. To address this, we present a dynamic eco-driving system (EDS) for a (host) vehicle based on model predictive control (MPC) with fuzzy-tuned weights, which helps efficiently utilize the gravitational potential energy. The objective function's weight is tuned via fuzzy inference techniques using information of the vehicle's instantaneous velocity and the road slope angle. By considering the vehicle longitudinal dynamics, preceding vehicle's state, and road slope information (obtained from the digital road map), the optimization generates velocity trajectories for the host vehicle that minimizes fuel consumption and CO2 emission. The effectiveness of the proposed EDS is evaluated using microscopic traffic simulations on a real road stretch in Fukuoka City, Japan, and the results demonstrate that the fuzzy-tuned MPC EDS significantly reduces fuel consumption and CO2 emission of the host vehicle compared to the traditional driving (human-based) system (TDS) for the same travel time.

Ref.: A.S.M. Bakibillah, M.A.S. Kamal, Chee Pin Tan, Tomohisa Hayakawa, Jun-ichi Imura, Fuzzy-tuned model predictive control for dynamic eco-driving on hilly roads, Applied Soft Computing, vol. 99, 106875, 2021.

Cyber-based Parking Management System Towards Smart Livings

Existing parking management approaches do not consider specific requirements, priorities, user comfort, or modes of use when allocating a parking spot in a large park. As a result, vehicles carrying multiple passengers but staying for a limited period often have to drive further, searching for a parking spot, which increases fuel consumption, emissions, waste of time, and discomfort of users due to extra walking distance. In this work, we consider the need for both sustainability and comfortable livings in a future smart city and propose an adaptive-optimal scheme that takes advantage of parking efficiency based on the passenger information and flexibly provides the optimal parking spot to the individual. The decision process is fine-tuned using parking data obtained from a model of a large car park of a shopping complex, and the results of the proposed scheme are compared with other schemes.

Ref.: Taiga, S., Bakibillah, A., Hashikura, K., M.A.S. Kamal, & Yamada, K. (2021). A User-Oriented Adaptive-Optimal Car Parking Management System Towards Smart Livings. International Journal of Engineering Materials and Manufacture, 6(3), 202–208.

AI-enabled conceptual framework for Multiple vehicle cooperation and collision avoidance in automated vehicles

Beside traffic and vehicle control expectations, customers are becoming more concerned about safety and comfort as the automobile industry swings toward automated vehicles (AVs). A comprehensive evaluation of recent AVs collision data indicates that modern automated driving systems are prone to rear-end collisions, usually leading to multiple-vehicle collisions. This work reviewed diverse techniques of existing literature to provide planning procedures for multiple vehicle cooperation and collision avoidance (MVCCA) strategies in AVs while also considering their performance and social impact viewpoints. Firstly, we investigate and tabulate the existing MVCCA techniques associated with single-vehicle collision avoidance perspectives. Then, current achievements are extensively evaluated, challenges and flows are identified, and remedies are intelligently formed to exploit a taxonomy. This study also aims to give readers an AI-enabled conceptual framework and a decision-making model with a concrete structure of the training network settings to bridge the gaps between current investigations. These findings are intended to shed insight into the benefits of the greater efficiency of AVs set-up for academics and policymakers.

Ref.: Muzahid, A.J.M., Kamarulzaman, S.F., Rahman, M.A., Murad, S.A., Kamal, M.A.S. and Alenezi, A.H., Multiple vehicle cooperation and collision avoidance in automated vehicles: survey and an AI-enabled conceptual framework. Sci Rep 13, 603 (2023).

５．主な発表論文等

〔雑誌論文〕　計10件（うち査読付論文　10件／うち国際共著　10件／うちオープンアクセス　7件）

１．著者名 Kamal Md Abdus Samad、Hashikura Kotaro、Hayakawa Tomohisa、Yamada Kou、Imura Jun-ichi	４．巻 71
２．論文標題 Look-Ahead Driving Schemes for Efficient Control of Automated Vehicles on Urban Roads	５．発行年 2022年
３．雑誌名 IEEE Transactions on Vehicular Technology	６．最初と最後の頁 1280～1292
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TVT.2021.3132936	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Kamal Md Abdus Samad、Hashikura Kotaro、Hayakawa Tomohisa、Yamada Kou、Imura Jun-ichi	４．巻 12
２．論文標題 Adaptive Cruise Control with Look-Ahead Anticipation for Driving on Freeways	５．発行年 2022年
３．雑誌名 Applied Sciences	６．最初と最後の頁 929～929
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/app12020929	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Yamada Yu、Bakibillah Abu Saleh Md、Hashikura Kotaro、Kamal Md Abdus Samad、Yamada Kou	４．巻 14
２．論文標題 Autonomous Vehicle Overtaking: Modeling and an Optimal Trajectory Generation Scheme	５．発行年 2022年
３．雑誌名 Sustainability	６．最初と最後の頁 1807～1807
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/su14031807	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Bakibillah A. S. M.、Kamal Md Abdus Samad、Tan Chee Pin、Susilawati Susilawati、Hayakawa Tomohisa、Imura Jun-ichi	４．巻 21
２．論文標題 Bi-Level Coordinated Merging of Connected and Automated Vehicles at Roundabouts	５．発行年 2021年
３．雑誌名 Sensors	６．最初と最後の頁 6533～6533
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/s21196533	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Ng Christina、Susilawati Susilawati、Samad Kamal Md Abdus、Leng Chew Irene Mei	4．巻 2021
2．論文標題 Development of Macroscopic Cell-Based Logistic Lane Change Prediction Model	5．発行年 2021年
3．雑誌名 Journal of Advanced Transportation	6．最初と最後の頁 1～17
掲載論文のDOI（デジタルオブジェクト識別子） 10.1155/2021/7905609	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Bakibillah Abu Saleh Md、Paw Yi Feng、Kamal Md Abdus Samad、Susilawati Susilawati、Tan Chee Pin	4．巻 4
2．論文標題 An Incentive Based Dynamic Ride-Sharing System for Smart Cities	5．発行年 2021年
3．雑誌名 Smart Cities	6．最初と最後の頁 532～547
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/smartcities4020028	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Akhand M. A. H.、Habib Md. Ahsan、Kamal Md Abdus Samad、Siddique Nazmul	4．巻 11
2．論文標題 Physarum-Inspired Bicycle Lane Network Design in a Congested Megacity	5．発行年 2021年
3．雑誌名 Applied Sciences	6．最初と最後の頁 6958～6958
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/app11156958	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Taiga Sato、Bakibillah A.S.M.、Hashikura Kotaro、Samad Kamal Md Abdus、Yamada Kou	4．巻 6
2．論文標題 A User-Oriented Adaptive-Optimal Car Parking Management System Towards Smart Livings	5．発行年 2021年
3．雑誌名 International Journal of Engineering Materials and Manufacture	6．最初と最後の頁 202～208
掲載論文のDOI（デジタルオブジェクト識別子） 10.26776/ijemm.06.03.2021.12	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Kamal Md Abdus Samad、Tan Chee Pin、Hayakawa Tomohisa、Azuma Shun-Ichi、Imura Jun-Ichi	4．巻 99
2．論文標題 Control of Vehicular Traffic at an Intersection Using a Cyber-Physical Multi-Agent Framework	5．発行年 2021年
3．雑誌名 IEEE Transactions on Industrial Informatics	6．最初と最後の頁 1〜1
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TII.2021.3051961	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Bakibillah A.S.M.、Kamal M.A.S.、Tan Chee Pin、Hayakawa Tomohisa、Imura Jun-ichi	4．巻 99
2．論文標題 Fuzzy-tuned model predictive control for dynamic eco-driving on hilly roads	5．発行年 2021年
3．雑誌名 Applied Soft Computing	6．最初と最後の頁 106875〜106875
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.asoc.2020.106875	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計10件（うち招待講演　3件／うち国際学会　10件）

1．発表者名 M. A. S. Kamal, K. Hashikura, and K. Yamada
2．発表標題 look-ahead lane change scheme for efficient driving in freeway traffic
3．学会等名 Proc. of the 6th IFAC Conference on Engine and Power-train Control, Simulation and Modeling（国際学会）
4．発表年 2021年

1．発表者名 Y. Sakaguchi, A. S. M. Bakibillah, K. Hashikura, M. A. S. Kamal, and K. Yamada
2．発表標題 evelopment of an optimal traffic coordination system for connected and automated vehicles
3．学会等名 the Joint 2021 5th Intl. Conf. on Imaging, Vision & Pattern Recognition (IVPR) and 10th Intl. Conf. on Informatics, Electronics & Vision (ICIEV)（国際学会）
4．発表年 2021年

１．発表者名
N. Saki, M. A. S. Kamal, S. N. IBRAHIM, and M. M. H. MAHFUZ,

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sign a coaxial feed micro- strip patch antenna for vehicular communication

３．学会等名
Proc. of the Joint 2021 5th Intl. Conf. on Imaging, Vision & Pattern Recognition (IVPR) and 10th Intl. Conf. on Informatics, Electronics & Vision (ICIEV)（国際学会）

４．発表年
2021年

１．発表者名
M. N. Shakib, M. Shamim, M. N. H. Shawon, M. K. F. Isha, M. Hashem and M. A. S. Kamal

２．発表標題
An adaptive system for detecting driving abnormality of individual drivers using gaussian mixture model

３．学会等名
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2021年

１．発表者名
Most. Kaniz Fatema Isha Khulna University of Engineering & Technology, Khulna, Bangladesh ; Md. Nazirul Hasan Shawon; Md. Shamim; Md. Nazmus Shakib; M.M.A. Hashem; M.A.S. Kamal

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2021年

１．発表者名
Motasim Billah Mredul, Md. Ahsan Habib, M. A. H. Akhand and M. A. S. Kamal

２．発表標題
Network Repair Crew Scheduling Using Benders Decomposition Method: A Case Study of Dhaka City

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４．発表年
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１．発表者名
A. S. M. Bakibillah, M. A. S. Kamal and C. P. Tan

２．発表標題
Sustainable Eco-driving Strategy at Signalized Intersections from Driving Data

３．学会等名
2020 59th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE)（国際学会）

４．発表年
2020年

１．発表者名
Md Abdus Samad Kamal

２．発表標題
Smart-Driving in Partially Connected Vehicle Environment using Nonlinear Model Predictive Control

３．学会等名
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４．発表年
2020年

１．発表者名
Md Abdus Samad Kamal

２．発表標題
Cooperative Control of Connected-Automated Vehicles at Intersections Using Nonlinear Model Predictive Control

３．学会等名
The SICE Annual Conference 2020 (SICE 2020), Chiang Mai, Thailand（招待講演）（国際学会）

４．発表年
2020年

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Md Abdus Samad Kamal

２．発表標題
Cooperative- Driving of Connec- ted Automated Vehicles for Harmonizing Traffic Flows

３．学会等名
International Conference on Intelligent Technology, System and Service for Internet of Everything (ITSS-IoE 2021), China（招待講演）（国際学会）

４．発表年
2020年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

After starting the collaboration and having joint research outcomes under this project, Gunma University signed a Memorandum of Understanding (MoU), each with Monash University Malaysia and Khulna University of Engineering and Technology, Bangladesh. We hope to continue various joint research with these international collaborative universities and new ones in the coming years. The project yielded outcomes with many high-impact journal publications beyond the initial expectations in the given periods considering various aspects.

6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
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研究協力者	Akhand Md. Aminul Haque (Akhand Md. Aminul Haque)	Khulna University of Engineering and Technology・Computer Science and Engineering・Professor	
研究協力者	Susilawati Susilawati (Susilawati Susilawati)	Monash University・School of Engineering・Senior Lecturer	
研究協力者	Tan Chee Pin (Tan Chee Pin)	Monash University・School of Engineering・Senior Lecturer	
研究協力者	Kamarulzaman Syafiq Fauzi (Kamarulzaman Syafiq Fauzi)	Universiti Malaysia Pahang, Malaysia・Faculty of Computing・Associate Professor	

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関