Efficient Embedded Computing Component for Anti-Lock Braking System

Yair Wiseman

Computer Science Department
Bar-Ilan University, Ramat-Gan 52900, Israel
wiseman@cs.biu.ac.il

Abstract

Anti-lock Braking System - ABS is a monitoring system aims at preventing locking of vehicle wheels during an emergency braking. When the brake pedal is intensely pressed, the vehicle wheels can be locked and as a result the steering capability will be very poor, the stopping distance may possibly be getting longer and the friction can significantly wear off the vehicle tires. A good Anti-lock Braking System device can address these faults by unlocking the wheels. This paper proposes an efficient embedded computing component for anti-Lock braking system with the intention of improving the contemporary Anti-lock Braking Systems.

1. Introduction

Braking systems of vehicles generate friction of the brake pads against surfaces attached to the wheel with the aim of slowing the vehicle's speed by converting the kinetic energy of the vehicle to heat [1]. However, intense braking in high speed on slippery roads or even semi-slippery roads because of ice, oil or other reasons can be very dangerous [2].

With the move to autonomous vehicles [3] underway, many functions of vehicles turn into automatic [4]. One of them is the Anti-Lock Braking System that automatically reduces braking force in a case of locked wheels.

A vehicle without an Anti-Lock Braking System (ABS) [5] attempts to brake on slippery roads can completely stop its wheels. Such wheels are called locked wheel [6]. A locked wheel skids on the roads instead of going circularly can harm and even eliminate several critical functions of the vehicle:

- Loss of steering ability [7]: Steering is performed by combination of two elements - the steering wheel angle and the rolling tires. If the front wheels are locked, the steering ability of the vehicle will be lost. The driver will be able to turn the wheel effortlessly and the tires will indeed turn to the decided direction; however, the vehicle will not turn to the desired direction, but rather will keep move forward.
- Lengthening the stopping distance [8]: The angle of the wheels may possibly place the side of the tire against the road. The side of the tire has a lower traction than the center of the tire, so as a result the stopping distance will be lengthened.
- Increased wear [9]: When a tire skids on a road, the friction between the tire and the road will slow down the vehicle instead of slowing down the vehicle by the usual way *i.e.*, a friction with the braking pads. Additionally, this

friction between the tire and the road, will significantly wear off the tire [10,11,12]. Such a vehicle with worn out tire will also have a longer stopping distance, because the friction will generate a molten rubber in the tire which has an inferior traction.

Anti-Lock Braking System (ABS) prevents slippage and facilitates control of steering by continuously sampling the speed of the wheels and comparing them to the speed of the vehicles. If an abnormality slowdown of a wheel that is not with accordance of the vehicle speed is detected, temporary brake pauses will be taken so as to resume the desired speed.

The method that shortens the braking distance to the minimum possible is the one in which the maximum traction is used to create a braking power. This point of the brakes is on the verge of locked wheels and it is called "threshold braking" [13] i.e. on the verge of locking.

Most modern ABS devices operate efficiently and accurately detect the threshold braking. The main advantage of ABS is on smooth roads like wet roads where the system is able to significantly and considerably shorten the stopping distance. In addition, ABS keeps the vehicle in control of the driver who will be able to maneuver in order to avoid obstacles, if the stopping distance is insufficient to stop the vehicle before it hits the obstacles. There are also security implementations for this technology [14].

2. The Embedded Computing Component of Anti-Lock Braking System

The key challenge of anti-lock braking systems is how to detect the situation of an abnormality slowdown of a wheel that is not with accordance of the vehicle speed. Some mechanical devices and also some electronic devices have been suggested during the years [15]. We suggest to extract from conventional computer blueprints some known components and to build from these components a control unit that will be able to detect the situation of an abnormality slowdown of a wheel that is not with accordance of the vehicle speed.

An ABS is depicted in Figure 1. The ABS includes four wheel speed sensors which work as follow: A cogwheel is attached to each wheel. Each tooth of the cogwheel is magnetized. The sensors have a galvanometer which produces values according to the closeness of the teeth. When there is a tooth nearby the galvanometer, the galvanometer will generate a higher voltage, whereas when the teeth are not nearby the galvanometer, almost no voltage will be generated [16]. The output of the galvanometer is depicted in Figure 2.

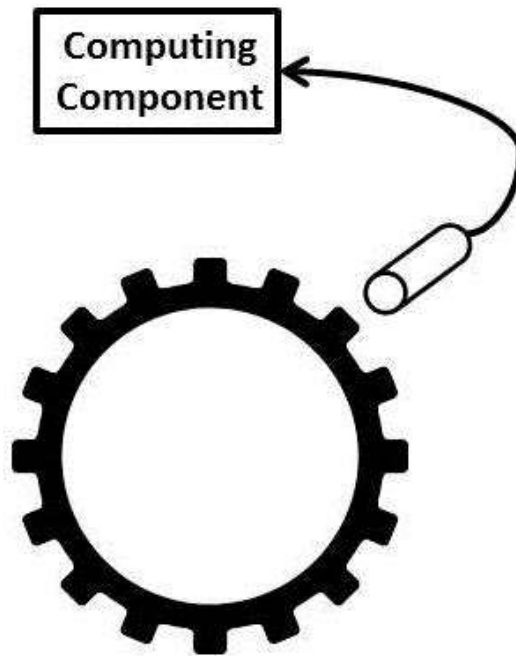The frequency of the changes in the output is depending on the rotation speed of the wheels.

Figure 1. ABS Using a Galvanometer and a Cogwheel

An ABS system has also four hydraulic valves within the brake hydraulics and an embedded computing component [17]. The embedded computing component repetitively observes the rotational speed of all the vehicle wheels and compares it to the vehicle speed. If the embedded computing component detects a wheel rotating much slower than the vehicle speed, it will put into action the valves so as to reduce hydraulic pressure to the brake of this wheel, with the intention of reducing the braking force on this wheel, so that the locked wheel will be released.

Contrariwise, if the embedded computing component detects a wheel turning much faster than the vehicle speed, it will augment the brake hydraulic pressure to this wheel with the aim of slowing down the wheel.

This comparison is repetitively performed in a rate of some hundredths of a second. As a result, it will be unfeasible to lock wheels of cars equipped with ABS even in the course of excessive braking.

On the other hand, the embedded computing component should be not so conscious to every difference in the wheel rotational speed. If a vehicle turns right, the wheels in the right side of the vehicle will turn slower than the wheels in the left side of the vehicle. Similarly, if a vehicle turns left, the wheels in the left side of the vehicle will turn slower than the wheels in the right side of the vehicle. The embedded computing component should not change the brake hydraulic pressure to any wheel because of these differences [18].

3. Implementation

The challenge of the embedded computing component of anti-lock braking system is how to detect a difference in the rotational speed of the wheels and the vehicle speed that reflects a locked wheel and does not reflect just a variance results from a turn to right or left.

For putting our ABS into practice, we have used Hyundai I30 CW 2017 for our implementation. The tires of this vehicle are P195/65R15 which means the sidewall height is 195*0.65mm i.e. 12.675cm. The 15 in the end of the code means diameter

in inches of the wheel that this tire is designed to fit i.e. 38.1cm. So the entire diameter of the tire plus the wheel is:

Diameter=12.675*2+38.1=63.45cm

Accordingly, the perimeter is 1.99334 meters. If this vehicle travels at a speed of 72 KM/H (45 MPH) i.e. 20 meters per seconds, it means that it will wholly rotate the tire 10 times each second.

We used a cogwheel of 16 teeth for both the vehicle and the wheels. We used sampling rate of 8 teeth of the vehicle cogwheel. In a speed of 72 KM/H (45 MPH) it will be a sample rate of 20 times per seconds, whereas in a speed of 144 KM/H (90 MPH), it will be a sample rate of 40 times per seconds.

The slip ratio of moving vehicle (i.e. when the vehicle speed is not zero) is defined as:

Slip ratio = (vehicle speed – wheel speed)/vehicle speed

If the slip ratio is 1 i.e. vehicle speed and the wheel speed are equal, it will mean that no lock occurs. Contrariwise, slip ratio of 0 i.e. wheel speed is 0, will mean an absolutely locked wheel.

It depends on road surface and tire condition, but from slip ratio of approximately 25%-30%, the slippage can set off the bad influence of poor stirring, longer stopping distance and increased wear.
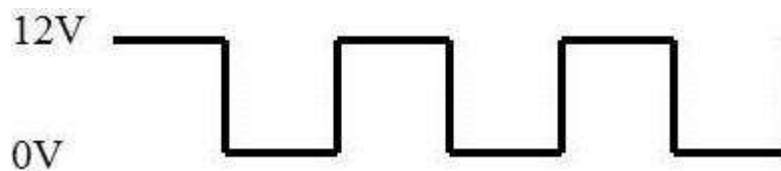

Figure 2. Output of the ABS Galvanometer

Accordingly, the ABS checks for every shifting of 8 teeth in the vehicle cogwheel, whether the cogwheel of the tire shifts at least 6 teeth. If a cogwheel of one tire shifts 5 teeth or less, it will indicate that a lock takes place; therefore the braking force of this tire will be decreased.

Contrariwise, if the cogwheel of one tire shifts 8 teeth for 8 teeth of the cogwheel of the vehicle, i.e. the slip ratio is 1, the braking force can be increased, because it indicates that at this time no slippage takes place.

Figure 3 depicts the circuit for detecting these cases of decreasing the braking force and increasing the braking force. The circuit has 2 input lines and 2 output lines. The input lines are the outputs of the galvanometers reading the cogwheels of the vehicle and the outputs of the galvanometers reading the cogwheels of the wheels. The forms of the input lines are depicted in Figure 2.

These input lines go to asynchronous counters that count the pulses of the galvanometers produce.

The output lines make the decisions when to decrease or increase the barking force. They are calculated only when the counter of the vehicle gets to 7 i.e. 111 in binary. If a cogwheel of one tire shifts 5 teeth or less, the decrease barking force output line of this tire will be 1 which indicates a decrease of the braking force because of a locked wheel. If a cogwheel of one tire shifts 8 teeth, the increase barking force output line of this tire will be 1 which indicates an increase of the braking force, because the wheel is completely unlocked.

If a cogwheel of one tire shifts 6 or 7 teeth, none of the output lines of this tire will be 1, because the lock is not acute and the stirring will not be poor, but on the other hand an increase in the braking force can harm the stirring capability, so the braking force remains unchanged.

The implementation of the upper line in Figure 3 which indicates a decrease of the braking force has been designed based on the Karnaugh map [19] in Figure 4 that gives the expression:

$$\text{Decrease force} = \overline{\overline{Q_2} + \overline{Q_1} \cdot \overline{Q_0}} = \overline{\overline{Q_2} + \overline{Q_1} + \overline{Q_0}}$$

The implementation of the lower line in Figure 3 which indicates an increase of the braking force is quite trivial. It will give 1 just when all the lines of the wheel velocity counter are 1 like the lines of the vehicle velocity counter, so that gives the straightforward expression:
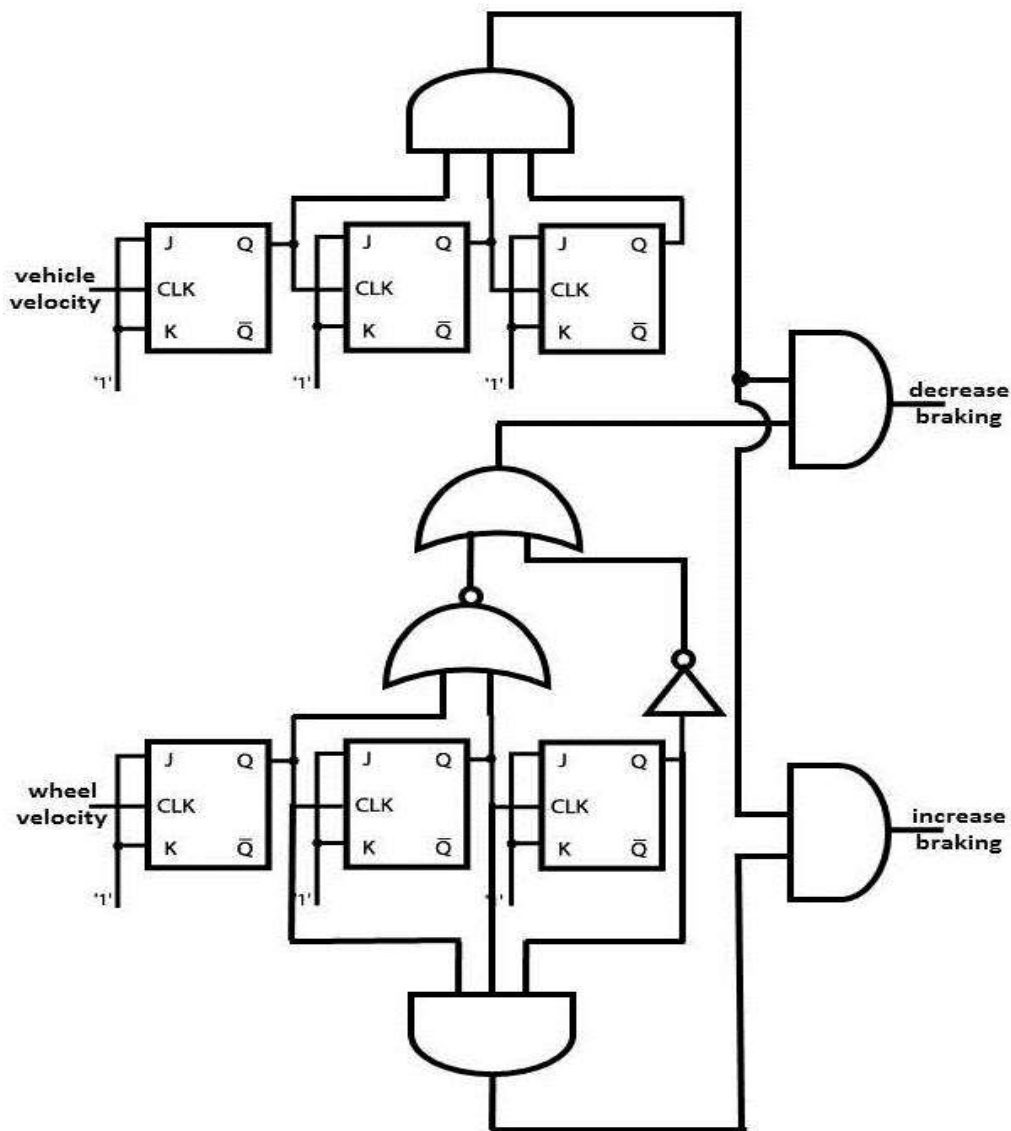
$$\text{Increase force} = Q_2 + Q_1 + Q_0$$

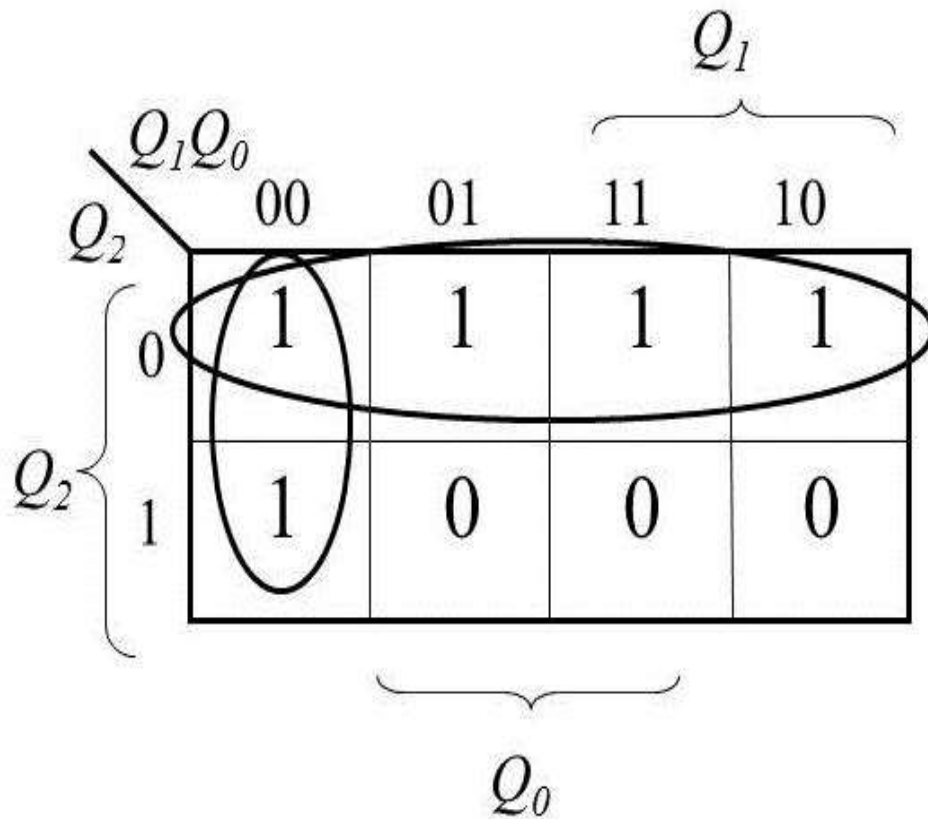**Figure 3. Computing Component for Detecting the "locking" Level**

Figure 4. Karnaugh Map for Braking Force Decrease

4. The ABS Counter

The two groups of 3 flip-flops in Figure 3 actually form two asynchronous counters. Asynchronous counters consist of JK flip-flops or T flip-flops whose inputs are connected to a voltage that represent the logical value of "1" [20]. When there is a change in the clock, the "1" input will set the current output of the flip-flops to be the inverse of its previous value. Each of the flip-flops stores one bit, so the entire counter can count from 0 to 2^n-1 where n is the number of the flip-flops in the counter. Then, the counter's value will return to 0 instead of 2^n. Actually an overflow occurs in the counter, but it is usually ignored.

The value stored in the left flip-flop will change in each clock cycle; therefore it will take two clock cycles until the left flip-flop returns to its original value. In each clock cycle, the left flip-flop's value will be changed from 0 to 1 or from 1 to 0, so as a result, the output of the left flip-flop generates another clock cycles whose frequency is a half of the original clock cycle frequency, that is, the duration of the second clock cycles is as twice as the duration of the original clock cycles. The double duration clock is connected as the clock cycles of the second flip-flop. The second flip-flop is like the first flip-flop, a one-bit counter, but its frequency is a half of the frequency of the first flip-flop. Similarly, the output of the second flip-flop is connected as the clock cycles of the third flip-flip that its frequency will be a half of the frequency of the second flip-flop.

Such a combination of several flip-flops together produces a several bit counter, as we used in our implementation in Figure 3. Particularly, each of the two counters in Figure 3 consists of three flip-flops where Bit 0 is the left flip-flop which toggles the fastest and Bit 2 is the third flip-flop which toggles the slowest. The range of the numbers in these flip-flops is 0-7.

The use of the flip-flops' outputs as a clock causes time discrepancies between the bits of the counter, because when a counter value is modified, initially the flip-flop that stores Bit 0 will be modified and it will take some more time until a possible modification is propagated to the rest of the flip-flops in the counter [21]; therefore, this counter is called asynchronous counter.

Because of this modification characteristic, asynchronous counter is not suitable for use in conventional synchronous circles where all components are modified at the same time by a single clock signal; thus, a short modification time is imperative. A modification that propagates in linear time in the number of the flip-flops is likely to be too slow for several implementations; however, in the implementation of ABS, anyway the clock cycle frequency is slow enough, so such a longer modification time will not make a problem.

The most important usage of ABS is in fast moving. In slow movement like during a parking [22,23] or a vehicle creeping forward in a traffic jam [24,25,26], the possibility of locked wheel is more than slim.

As was calculated above, if the vehicle travels at a speed of 72 KM/H (45 MPH) i.e. 20 meters per seconds, it means that it will wholly rotate the tire 10 times each second and in a enormous speed of 450 KM/H (281 MPH), it will wholly rotate the tire 62.5 times each second. Since the cogwheel has 16 teeth, it will have even in the enormous speed of 450KM/H, a clock rate of just 1KH. The delay time of common flip-flops is just few nanoseconds [27], so accordingly there is no problem to use asynchronous counters in ABS.

4. The ABS State Machine

Like the implementation of many other Intelligent Transportation Systems [28,29], the Embedded Computing Component of the ABS includes a Moore state machine [30]. The state machine is depicted in Figure 5.

The input lines of the machine come from the circuit in Figure 3. The lines are increase braking and decrease braking and they are abbreviated as i.b. and d.b. in Figure 5.

As the state machine is Moore machine, the output is set only according to the current state. The output goes to the hydraulic valve and sets the braking force. If the braking force is 100% and a decision about reduce braking force is taken, the reduction will be higher i.e. to 80% than if the braking force is 20% and a decision about reduce braking force is taken. In 20%, it will be only to 10%. In general, the higher percent the braking force is, the higher the reduction will be.
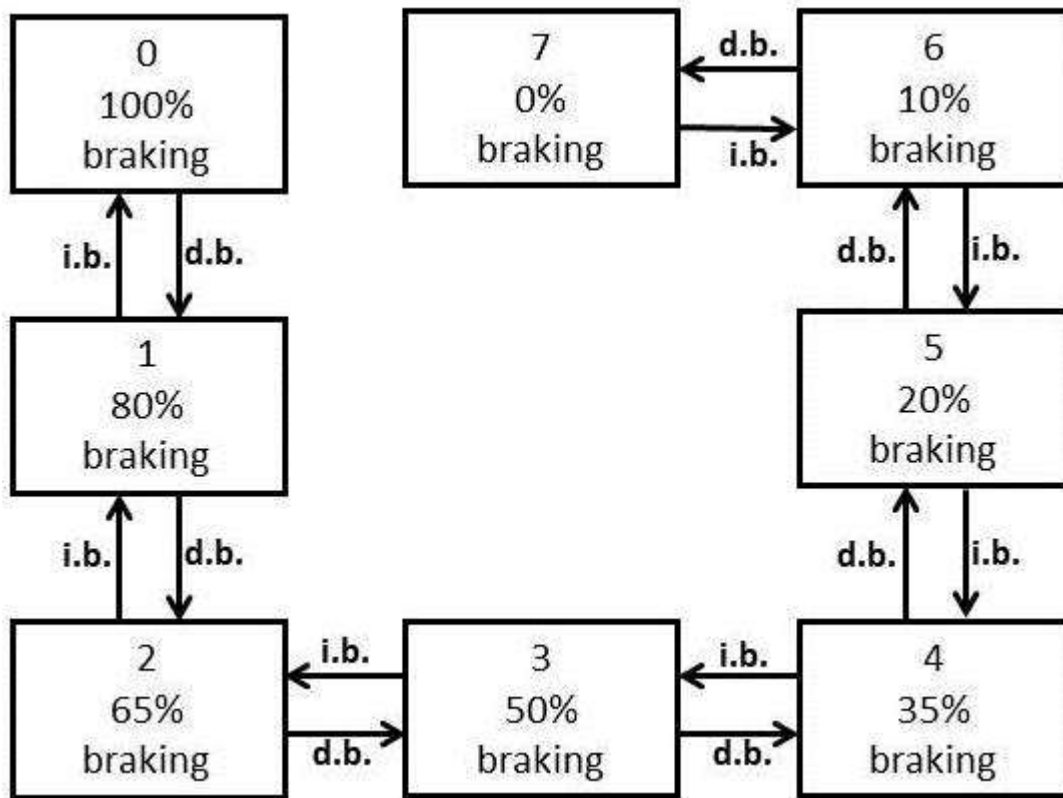
Figure 5. ABS State Machine

6. Conclusions

The proposed ABS device can be implemented in both regular vehicles and autonomous vehicles, so as to have more efficient embedded computing component. This better efficiency is an important advantage in avoiding vehicle accidents [31,32,33,34], because locked wheels or even semi-locked wheel [35] may possibly lead to a poor steering capability causing a collision and as a result, a fatal accident might occur [36,37], so the ABS should be as accurate as possible so as to avoid accidents and save lives.

References

[1] Chan and G. W. Stachowiak, "Review of Automotive Brake Friction Materials", Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol. 218, no. 9, **(2004)**, pp. 953-966.

[2] M. C. Wu and M. C. Shih, "Simulated and Experimental Study of Hydraulic Anti-Lock Braking System Using Sliding-Mode PWM Control", Mechatronics, Elsevier, vol. 13, no. 4, **(2003)**, pp. 331-351.

[3] Y. Wiseman, "Autonomous Vehicles", Encyclopedia of Organizational Knowledge, Administration, and Technologies, **(2019)**, Available online at: http://u.cs.biu.ac.il/~wiseman/autonomousr.pdf

[4] Y. Wiseman, "Ancillary Ultrasonic Rangefinder for Autonomous Vehicles", International Journal of Security and its Applications, vol. 12, no. 5, **(2018)**, pp. 49-58.

[5] Z. Lin, L. Yuegang, K. Jing and S. Zhanqun, "Anti-lock Braking System", Proceedings of 2015 IEEE Sixth International Conference on Intelligent Systems Design and Engineering Applications (ISDEA), **(2015)**, pp. 151-154**.**

[6] D. W. Goudie, J. J. Bowler, C. A. Brown, B. E. Heinrichs and G. P. Siegmund, "Tire Friction During Locked Wheel Braking",Proceedings of SAE 2000 World Congress, SAE Technical Paper No. 2000-01-1314, **(2000)**.

[7] K. Matsuno, R. Nitta, K. Inoue, K. Ichikawa and Y. Hiwatashi, "Development of a New All-Wheel Drive Control System", Proceedings of 2000 FISITA World Automotive Congress, Seoul, Korea, **(2000)**.

[8]   D. Green, "A Comparison of Stopping Distance Performance for Motorcycles Equipped with ABS, CBS and Conventional Hydraulic Brake Systems", Proceedings of International Motorcycle Safety Conference, **(2006)**, pp. 26-30.

[9]   M. Wieczorowski, R. Mrozek and P. Andrałojć, "The Use of Surface Asperities Analysis to Investigate Wear of Bodies in Contact on Example of Brake Elements", Metrology and Measurement Systems, vol. 17, no. 2, **(2010)**, pp. 271-278.

[10] Y. Wiseman, "Take a Picture of Your Tire!", In Proceedings of The 12th IEEE Conference on Vehicular Electronics and Safety (IEEE ICVES-2010), Qingdao, ShanDong, China, **(2010)**, pp. 151-156.

[11] Y. Wiseman, "The Effectiveness of JPEG Images Produced By a Standard Digital Camera to Detect Damaged Tyres", World Review of Intermodal Transportation Research, vol. 4, no. 1, **(2013)**, pp. 23-36.

[12] Y. Wiseman, "Camera That Takes Pictures of Aircraft and Ground Vehicle Tires Can Save Lives", Journal of Electronic Imaging, vol. 22, no. 4, 041104, **(2013)**.

[13] L. D. Metz and R. R. Scheibe, "Use of ABS in Emergency Brake-and-Steer Maneuvers", In proceedings of SAE World Congress & Exhibition, SAE Technical Paper No. 2009-01-0449, Tire and Wheel Technology and Vehicle Dynamics and Simulation, **(2009)**.

[14] Y. Wiseman and Y. Giat, "Multi-modal passenger security in Israel", Multimodal Security in Passenger and Freight Transportation: Frameworks and Policy Applications, Edward Elgar Publishing Limited, Chapter 16, **(2016)**, pp. 246-260.

[15] A. A. Aly, E. S. Zeidan, A. Hamed and F. Salem, "An Antilock-Braking Systems (ABS) Control: A Technical Review", Intelligent Control and Automation, Scientific Research Publishing, vol. 2, no. 3, **(2011)**, pp. 186-195.

[16] M. Ortner, M. Ribeiro, M. Seger and A. Satz, "Guidelines for Cogwheel Design Optimized for Back-Bias Speed Sensor Applications", Proceedings of IEEE 2014 International Conference on Industrial Automation, Information and Communications Technology (IAICT), Inna Kuta Bali, Indonesia, **(2014)**, pp. 76-82.

[17] M. C. Wu and M. C. Shih, "Hydraulic Anti-Lock Braking Control Using The Hybrid Sliding-Mode Pulse Width Modulation Pressure Control Method", Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, vol. 215, no. 2, **(2001)** , pp. 177-187.

[18] S. Saito and K. Nonaka, "DYC and SMC Combined New Tracking Control Based on Nonholonomic Constraints for Skidding Cars", Proceedings of ASME 2005 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, pp. 2397-2406, **(2005)**.

[19] M. E. Holder, "A modified Karnaugh map technique", IEEE Transactions on Education, vol. 48, no. 1, **(2005)**, pp. 206-207.

[20] M. M. Mano and C. R. Kime, "Logic and computer design fundamentals", Pearson Prentice Hall, Upper Saddle River, NJ, **(2008)**.

[21] L. A. Lim, A. Ghazali, S. Chan, T. Yan and C. C. Fat, "Sequential circuit design using quantum-dot cellular automata (qca)", In proceedings of 2012 IEEE international conference on Circuits and systems (ICCAS), **(2012)**, pp. 162-167.

[22] Y. Wiseman, "Remote Parking for Autonomous Vehicles", International Journal of Hybrid Information Technology, vol. 10, no. 1, **(2017)**, pp. 313-324.

[23] Y. Wiseman, Self-Driving Car - A Computer will Park for You, International Journal of Engineering & Technology for Automobile Security, SERSC, Sandy Bay, Australia, vol. 1, no. 1, **(2017)**, pp. 9-16.

[24] Y. Wiseman, "Real-Time Monitoring of Traffic Congestions", The 17th IEEE International Conference on Electro Information Technology (EIT 2017), Lincoln, Nebraska, USA, pp. 501-505, **(2017)**.

[25] Y. Wiseman, "Computerized Traffic Congestion Detection System", International Journal of Transportation and Logistics Management, vol. 1, no. 1, pp. 1-8, **(2017)**.

[26] Y. Wiseman, "Tool for Online Observing of Traffic Congestions", International Journal of Control and Automation, vol. 10, no. 6, **(2017)**, pp. 27-34.

[27] S. Heo and K. Asanovic, "Load-sensitive flip-flop characterizations", In proceedings of IEEE Workshop on VLSI, **(2001)**, pp. 87-92.

[28] Y. Wiseman, "Conceptual Design of Intelligent Traffic Light Controller", International Journal of Control and Automation, vol. 9, no. 7, **(2016)**, pp. 251-262.

[29] Y. Wiseman, "Traffic Light with Inductive Detector Loops and Diverse Time Periods", Contemporary Research Trend of IT Convergence Technology, SERSC Australia, vol. 4, **(2016)**, pp. 166-170.

[30] M. Morrison and N. Ranganathan, "Design of a Moore Finite State Machine Using a Novel Reversible Logic Gate, Decoder and Synchronous Up-Counter", Proceedings of 2011 11th IEEE Conference on Nanotechnology (IEEE-NANO-2011), Portland, Oregon, USA, **(2011)**, pp. 1445-1449.

[31] Y. Wiseman and I. Grinberg, "The Trolley Problem Version of Autonomous Vehicles", The Open Transportation Journal, vol. 12, **(2018)**, pp. 105-113.

[32] Y. Wiseman and I. Grinberg, "Autonomous Vehicles Should Not Collide Carelessly", Advanced Science and Technology Letters, vol. 133, **(2016)**, pp. 223-228.

[33] Y. Wiseman and I. Grinberg, "When an Inescapable Accident of Autonomous Vehicles is Looming", International Journal of Control and Automation, SERSC Australia, vol. 9, no. 6, **(2016)**, pp. 297-308.

[34] Y. Wiseman and I. Grinberg, "Circumspectly Crash of Autonomous Vehicles", Proc. IEEE International Conference on Electro Information Technology (EIT 2016), Grand Forks, North Dakota, USA, **(2016)**, pp. 382-386.

[35] D. A. Danaher, T. J. Buss and J. K. Ball. "Operation of the Eaton VORAD Collision Warning System and Analysis of the Recorded Data", Society of Automotive Engineers (SAE) Technical Paper, No. 2009-01-2911, **(2009)**.

[36] I. Grinberg and Y. Wiseman, "Scalable Parallel Collision Detection Simulation", Proc. Signal and Image Processing (SIP-2007), Honolulu, Hawaii, **(2007)**, pp. 380-385.

[37] I. Grinberg and Y. Wiseman, "Scalable Parallel Simulator for Vehicular Collision Detection", International Journal of Vehicle Systems Modelling and Testing, Inderscience, vol. 8, no. 2, **(2013)**, pp. 119-144.

Author

Yair Wiseman. He received the M.Sc. (summa cum laude) and Ph.D. degrees from Bar-Ilan University, the first Post-Doctoral degree with the Hebrew University of Jerusalem, and the second Post-Doctoral degree with the Georgia Institute of Technology.

His research interests include autonomous vehicles, intelligent transportation systems, embedded systems, real-time systems, computational transportation science, operating systems, and process scheduling.

He has authored two books. He is on the editorial board of several journals, a member of dozens of conference committees and a reviewer of many scholarly journals.

He has been teaching in many institutes including Bar-Ilan University, The Hebrew University of Jerusalem and Israel Aircraft Industry and has been supervising many graduate students. An interesting point is that Albert Einstein is Dr. Wiseman's academic great-great-grandfather (i.e. the advisor of the advisor of the advisor of Dr. Wiseman's advisor).

He has collaborated with other partners and received research grants to run an active laboratory from inter alia Sun Microsystems, Intel, and Polak Foundation.

He is an international expert who has reviewed and evaluated several large projects of the European Union, Israel Science Foundation, Marie Skłodowska-Curie actions in Ireland, Ministry of Education and Science of Kazakhstan. His papers have been published in many venues around the world.