Using Flash Solid-State LiDAR Technology to Access Better and Lower-Cost Vehicle Profiling Data in E-Tolling Applications

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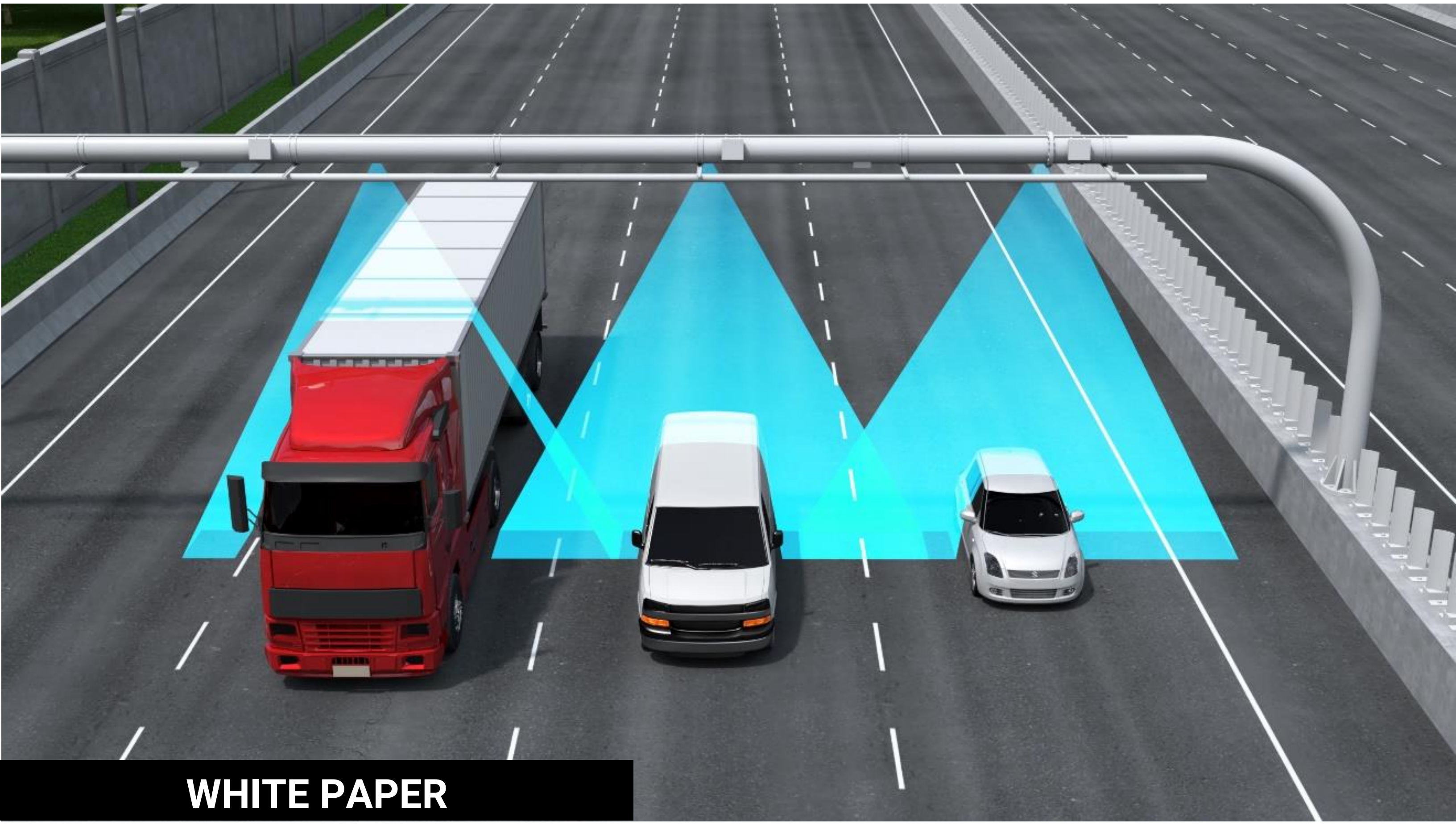

Abstract

As we enter a New Age for mobility, new enabling technologies are playing a key role in building transport systems that are safer, greener, and smarter. Among these technologies, detection and ranging sensors are paramount in enabling driver assistance, collision avoidance, or automation in various types of ITS solutions and vehicles. In electronic toll collection (ETC) systems, LiDARs are moving mainstream, providing distinct benefits over well-known sensing options such as cameras, radars, or ground loops.

Within the global tolling industry, free-flow tolling is steadily gaining ground thanks to being safer, greener, and more cost-effective than standard toll plazas. The fundamental challenges facing providers of electronic toll collection systems is the ability to deploy the most reliable, cost-efficient detection systems in order to ensure accurate vehicle detection, profiling, classification, and revenue collection. Moreover, ETC system owners tend to move away from intrusive detection systems (systems that affect the road infrastructure, such as ground loops) to favor non-intrusive above-ground detection systems.

This White Paper describes ways to improve vehicle profiling and their classification within free-flow tolling systems using non-intrusive sensing technologies, with a focus on using solid-state LiDAR as an alternative to incumbent sensors.

Challenges and limitations of current sensing technologies used in e-tolling will be addressed. We will provide an overview of the Flash solid-state LiDAR technology and its benefits compared to current technologies and demonstrate how it can be used to profile and classify vehicles. The use of machine learning will be discussed, too, with regards to enabling the full classification of vehicles, with a special emphasis on axle counting which, up to now, was only feasible with the use of road-intrusive technologies.

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1. Fundamentals of Vehicle Classification

Accurate vehicle classification is the cornerstone of electronic toll collection systems. Depending on the given road regulations, vehicles are assigned within a determined class of vehicles. It is very important for the ETC systems to accurately classify each vehicle, as wrong classification can result in undercharging road users, inducing revenue losses or, conversely, in overcharging them, which is a nuisance for the road users and results in preventable customer support and additional costs. Below is an overview of the characteristics that are used for appropriate vehicle classification.

- Number of axles: core classification characteristic of most toll classification systems
- Length and height: can also be used to further classify vehicles that have the same number of axles
- Number of trailers attached
- Width: seldom used yet as a classification criterion, width can be used to differentiate motorcycles from other vehicles, or to view if the vehicle exceeds the vehicle width limit of the road
- Weight: monitored for trucks and commercial vehicles for road durability protection and tax collection, the weighing is done mostly at weigh stations, which are commonly separate from free-flow ETC systems

2. Challenges and Limitations of Current ETC Technologies for Vehicle Profiling

The fundamental challenges facing providers of ETC systems is the ability to deploy the most reliable, cost-efficient detection systems to ensure accurate vehicle detection, profiling, classification, and revenue collection.

There are many sensing technologies and strategies to achieve vehicle classification that currently face several challenges and limitations.

2.1. Ground-Intrusive Sensor Challenges

One of the methods to classify vehicles is to count their number of axles. Currently, the mainstream detection technology to do so is ground-intrusive sensors, and most commonly ground induction loop-based systems.

2.1.1. High Operational Costs of Ground-Intrusive Sensors

Though their purchase price can be particularly appealing, induction loops remain costly to install, and the inherent stress put on them over time makes induction loops failure prone. Their installation and maintenance require invasive roadwork that affects road surface integrity. In addition, the inevitable lane closures involved during such installation and maintenance activities can be costly and might be highly problematic in more strategic or traffic-dense areas.

2.1.2. Tailgating Vehicles

ETC systems based exclusively on axle-counting methods for vehicle classifying might not be able to distinguish between tailgating vehicles (two vehicles closely following each other), a single longer vehicle, and/or a vehicle pulling a trailer. This limitation impacts the system's classification rate and directly translates to revenue loss, incorrect billing, and related customer service issues for overcharged users.

2.1.3. Vehicle Classification Limitations

Since they are installed at ground level, ETC systems based exclusively on axle-counting methods are limited with regards to the specific information they can provide about vehicles. Indeed, some vehicle classes can only be distinguished by their shapes, a piece of information which cannot be provided directly from ground level with axle counting. For example, inductive-loop traffic detectors cannot properly distinguish flatbed semi-trailers from semi-trailer trucks since their axles are identical and the difference lies in the trailer body.

2.1.4. Long-Term Reliability Issues

Any sensor failure in a tolling installation can impact its ability to properly operate. Over time, malfunctions can hurt the overall system performance and raise maintenance costs, negatively impacting operators' bottom lines.

2.2. Camera System Challenges

2.2.1. Sensitivity to Environmental and Weather Conditions

Environmental conditions, such as snow, rain, fog, and even road dust accumulation, can have a negative impact on some ETC technologies' ability to operate properly and maintain a high classification rate.

2.2.2. Slow Detection Rates

Depending on the sensor provider, a camera system can be limited in its vehicle classification capacity when vehicles pass at high speed. Depending on the local requirements, reliable classification by ETC needs to be unhindered up to 180 km/h.

2.2.3. Light Pollution

Camera systems will often require bright lighting in order to function in the absence of sunlight illumination. Such lighting can be intrusive and create "light pollution," especially when the ETC system is installed close to residential units.

3. LiDAR as a Viable, High-Performance ETC Detection Solution

Over the past few years, remote sensing companies have offered different alternative solutions to in-ground inductive loop for ETC systems in order to enable efficient vehicle classification. Among these, LiDARs have emerged as a promising option to solve the many issues faced with in-ground systems.

LiDAR is an active detection technology that functions similarly to a radar but uses the time of flight of light signals, instead of radio waves, to detect and profile objects. LiDARs can use two different types of light emission: collimated beams and diffused beams. A collimated beam is a light with rays that are parallel; it spreads minimally as it propagates. A perfectly collimated beam, with no divergence, will not disperse over distance. On the other hand, a diffused beam is a light that, as the name suggests, is diffused through emission options to spread the beam over the sensor's entire field of view (FoV).

There are two main types of LiDARs: mechanical scanning LiDARs, which use collimated beams, and Flash solid-state LiDARs, which use diffused beams. The pros and cons of each are illustrated below.

Figure 1 – Example of a Flash solid-state LIDAR for ETC applications

3.1. Mechanical Scanning LiDARs for ETC Applications

Mechanical scanning LiDARs use powerful collimated laser beams to concentrate the return signal on the receiver units through highly focused optics.

Simpler mechanical LiDARs use a single laser source that rotates and/or oscillates (usually with a motor) to capture a single horizontal line of data points at each cycle. More sophisticated mechanical LiDARs use an assembly of multiple emitter/receiver combinations (up to 128) that rotate mechanically to capture multiple horizontal lines of data points over up to 360 degrees.

However, some limitations of mechanical scanning LiDARs make them a less than ideal alternative solution for vehicle detection and profiling in modern ETC systems. The optical assembly's speed of rotation generally limits the measurement rates of such sensors to 100 Hz or less, thus affecting the system's ability to accurately detect tailgating vehicles, differentiate vehicle types at high speeds, and reliably detect hitches.

Moreover, the reduced signal sensitivity, in addition to the highly collimated beams of these sensors, impacts their ability to detect specular surfaces such as dark and non-reflective objects.

Mechanical LiDARs are also prone to performance deterioration in poor environmental conditions and weather due to their use of highly collimated lasers. A single drop of rain or a snowflake can significantly impact a collimated laser beam and send back misleading information for vehicle detection and profiling.

Finally, mechanical LiDARs, by their very nature, are assembled with multiple moving mechanical components, which triggers increased maintenance costs and reduces the overall lifespan of the system.

3.2. Flash Solid-State LiDAR

Various technologies are currently being implemented to provide solid-state LiDAR solutions (LiDARs which do not feature any moving parts). The most mature solid-state technology commercially available today is the Flash solid-state LiDAR (Flash SSL).

Flash SSL is similar in principle to a photography flash on a standard camera but sends over 100,000 light pulses per second. Each of these light pulses illuminates the entire FoV, covering 100% of the scene. In comparison, mechanical scanning LiDARs use collimated laser beams and rotate to scan an area, leaving several undetected zones in between each line and each data point captured.

After the light is reflected off an object, time-of-flight calculations allow the Flash-based sensor to accurately measure the distance and provide the angular resolution of the object using a solid-state photodiode array underneath the optical receptor. Flash LiDARs provide consistent and reliable object detection at a high measurement rate. This high object detection rate enables important ETC applications, such as vehicle detection and profiling, which require sensing speed, accuracy, and robustness at a reasonable price.

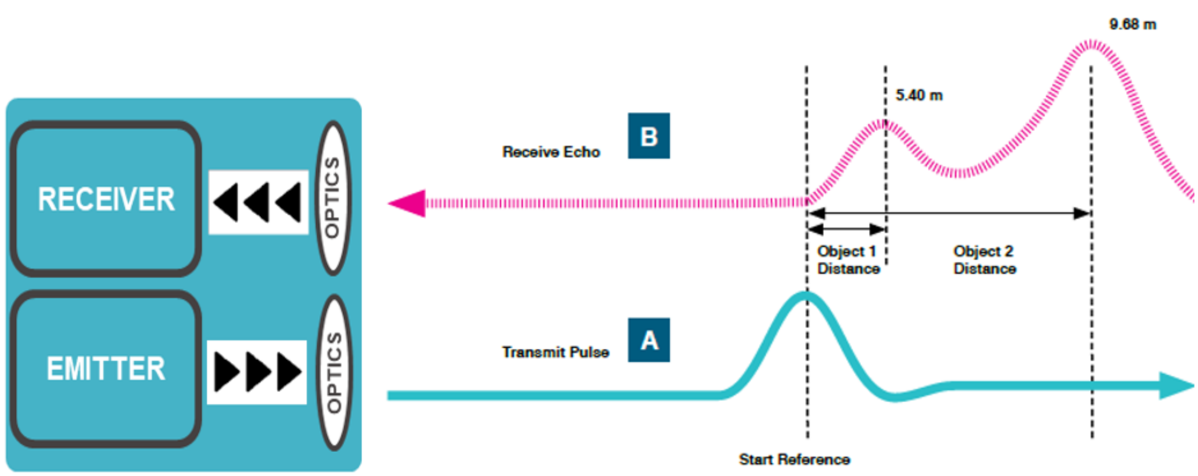


Figure 2 – Solid-state LiDAR acquisition process

Flash LiDARs' large, diffused light emission pattern also improves the detection rate over specular surfaces such as black cars as it translates into a higher probability to collect the returned light, thanks in part to a larger reception aperture.

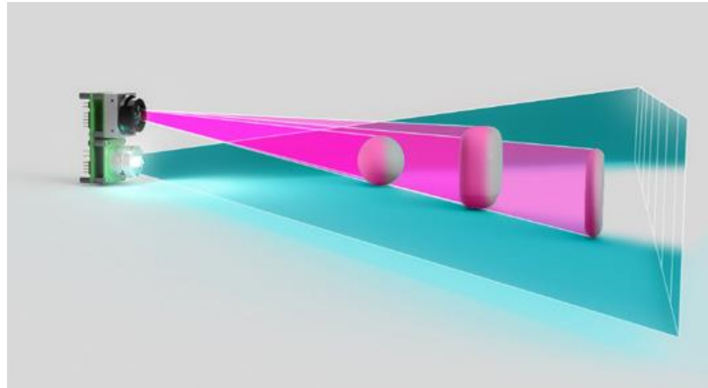


Figure 3 – Object detection with a Flash SSL module

Since Flash SSL solutions do not have the physical limitation of mechanical LiDARs, they are able to achieve higher measurement rates for better high-speed vehicle detection and profiling. In addition, Flash SSL systems also operate over a wider temperature range than most of their mechanical counterparts. For instance, Leddar-based LiDAR traffic sensors are specified to operate in an ambient operating temperature range of -40 °C to 60 °C compared to -30 °C to 50 °C for a mainstream mechanical LiDAR[1].

3.3. Benefits of Flash SSL Solutions for ETC System Operators

Flash SSL offers a value-added solution to ETC system operators and integrators that provides significant benefits previously unattainable with current sensing technologies.

3.3.1. Higher Classification Rates

Flash SSL offers accurate detection of tailgating vehicles, providing reliable 3D vehicle profiles, and ensuring a high detection rate on low-reflectivity objects and black cars. It provides a solution that significantly increases the classification rates of ETC systems.

3.3.2. No Revenue Loss

Flash SSLs' diffuse emission patterns offer better detection capabilities over objects that were historically hard to detect by LiDARs, such as black cars or low-reflectivity objects. Moreover, Flash SSLs maintain a high detection rate in harsh weather conditions, which significantly reduces the error rate and maximizes revenue.

3.3.3. Limited Lane Closures

ETC installations that rely entirely on Flash SSLs provide high MTBF, thereby limiting lane closure needs. Maintenance is also simplified to the above-ground, non-intrusive installation. The equipment can often be accessed from overhead and even be troubleshooted and fixed remotely.

1 Example of LeddarTech T16 traffic sensor compared to SICK LMS511.

3.3.4. Higher Potential Revenues

Overhead profiling systems are necessary to properly identify vehicle classes, because some differences can only be identified from above. Increasing the number of identifiable classes provides a major opportunity for ETC operators and system providers to generate more revenues.

3.3.5. Reduced Operational Expenses

Flash SSLs are more reliable than mechanical LiDAR solutions. Installed above ground on gantries, they also offer enhanced reliability and lower maintenance complexity costs compared to in-ground detection loops. As a result, maintenance, downtimes, and lane closures are reduced to a minimum, improving operator's bottom line over time.

The chart below presents the six most restrictive challenges typically faced in the ETC industry, along with solutions provided by Flash SSL to reduce or even eliminate them.

Table 1 – ETC industry's most frequent problems and related solutions from Flash SSL

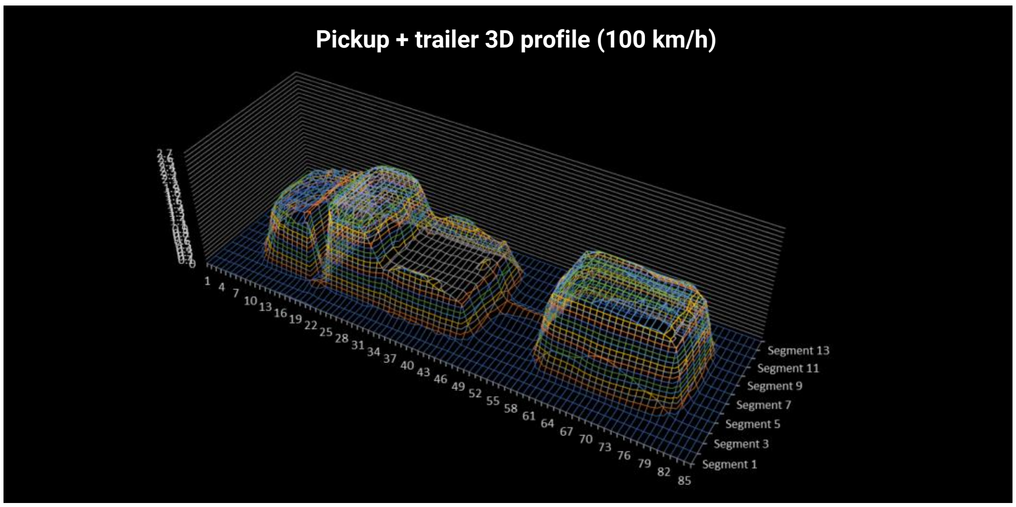
ETC Challenges	Flash LiDAR Solutions	Flash SSL Benefits and ROI
Tailgating vehicles	Precise 3D profiling capabilities and fast measurement rates improve vehicle separation and hitch detection.	• Higher classification rate • No revenue loss
Lane closures for in-ground installation and maintenance	Overhead installation for simpler maintenance Remote maintenance	• Limited lane closures
Errors in harsh weather conditions	Diffuse light emission and signal processing / noise filtering improve harsh weather performance.	• Higher classification rate • No revenue loss
Limited number of classes possible based on axle counting	Precise 3D profiling capability and fast measurement rates improve vehicle profiling and classification capabilities.	• Higher potential revenue
Low detection rates on dark vehicles	Large, diffuse light signal emissions, signal accumulation, and digital processing improve dark vehicle detection compared to other LiDARs.	• Higher classification rate • No revenue loss
High operational costs due to long-term reliability issues	Solid-state design increases LiDAR robustness, MTBF, and maintenance requirements.	• Higher reliability • Reduced operational costs

4. Vehicle Profiling with Flash SSL

Vehicle profiling using Flash SSL is very similar to profiling with other types of LiDAR scanning methods. Instead of generating a point cloud, a Flash LiDAR produces a 3D profile of the vehicles' surface. As the vehicle passes underneath the gantry and into the sensor's detection area, the height and width of the vehicle are acquired at a rate of 5 ms to 10 ms. As the data generated by each scan is accumulated over time, the 3D rendering of the vehicle's surface and shape takes form in a very similar way 3D printing is achieved. To obtain the length of the vehicle, its speed must also be acquired, which can be done with sensing technologies such as LiDAR or radar.

Below is an example of Flash SSL profiling, enabling efficient vehicle classification based on multiple differentiators such as vehicle height, width, length, and design details. This also allows system integrators to develop specialized classification algorithms with significant value-added potential, as these algorithms can be subsequently used by ETC operators.

The example below shows a 3D profile of a pickup truck traveling at 100 km/h with a trailer attached. It should be noted that the hitch is clearly visible in this representation, making it possible to readily identify the trailer as opposed to it being mistaken for a tailgating vehicle.



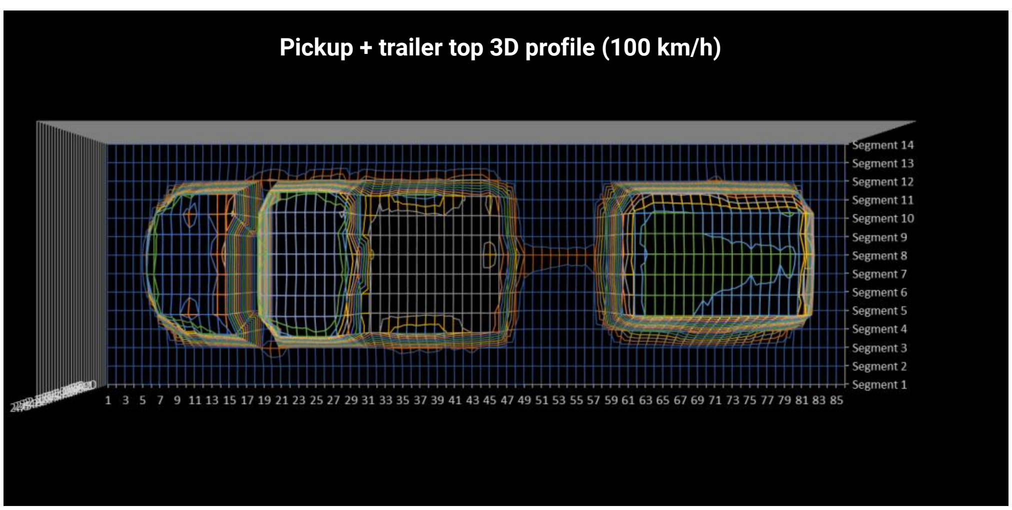


Figure 4 – 3D rendering of a pickup truck with a trailer traveling at 100 km/h using Leddar Flash SSL technology

4.1. Overhead Perpendicular LiDAR Setup

For vehicle profiling, it is recommended that the Flash SSL sensors be mounted to overhead structures, such as down-facing gantries perpendicular to the road, to allow the sensors to achieve optimal height and width resolution.

The following diagram shows a typical recommended installation with one or two sensors per lane mounted at a 90° angle, perpendicular to the ground. Including one Flash SSL sensor with at least a 45° FoV in the gantry setup will ensure coverage of the entire lane and detection of any straddling vehicles.

For an even better detection rate and overall dimension precision, including for vehicles that straddle two lanes, a different setup could be used with two types of sensors with narrower FoV: one sensor would be dedicated to each lane and a second sensor would cover each straddling point.

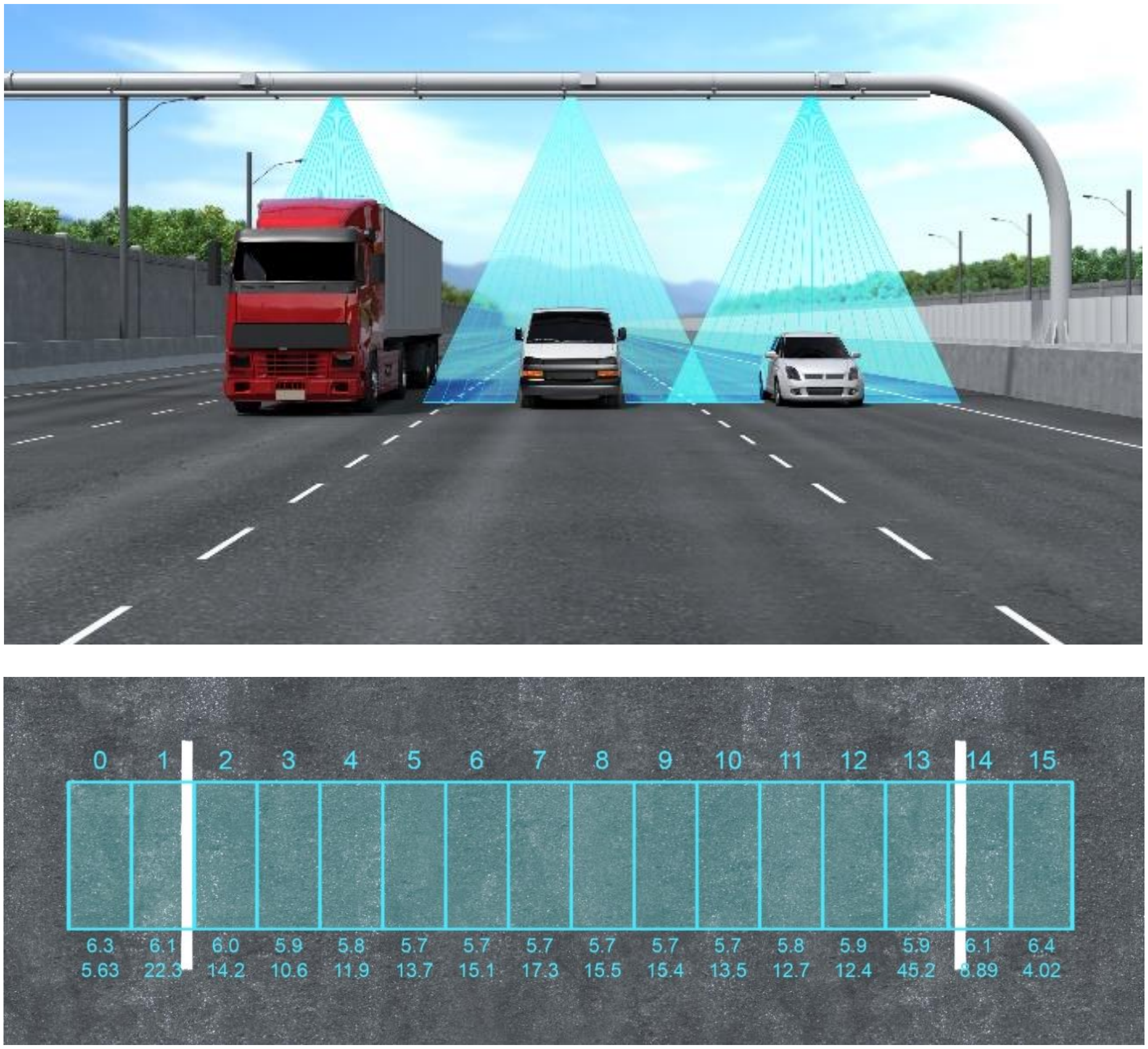


Figure 5 – Representation of the detection segments of a Flash SSL sensor for a recommended setup with one sensor per traffic lane

Hitch detection is also possible from a Flash SSL overhead installation, thanks to the sensors' high measurement rate and the 100% light density of the detected area.

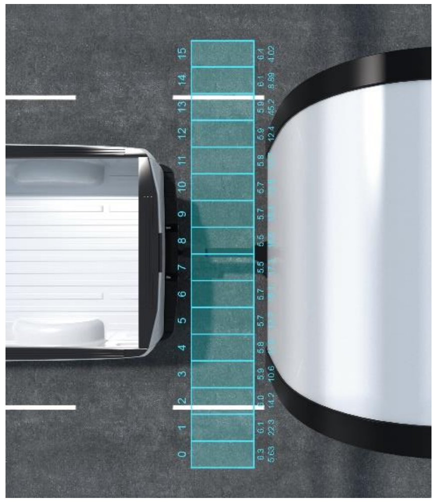


Figure 6 – Hitch detection using SSL technology

4.2. Overhead Oblique LiDAR Setup

Such configuration is part of the recent innovations being implemented within the ETC tolling industry. This innovation is being driven by the desire of ETC solution providers to step away from the issues encountered by ground-intrusive axle counting technologies.

The following figures show a recommended installation with one or two sensors per lane mounted with tilts of 90° and 45°. An angular resolution between 0.5° and 1° and refresh rate of 200 Hz must be achieved to precisely detect and count the axles.

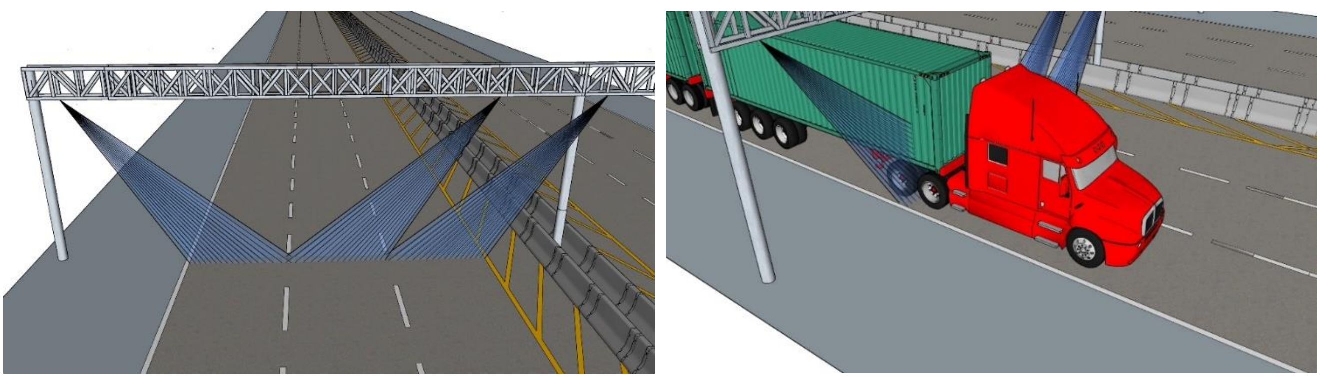


Figure 7 – Overhead oblique LiDAR setup

It is recommended to have the sensors mounted in opposite directions to prevent them from being blocked by a truck that would be overtaking another truck. With this configuration, cars that are overtaking trucks will not hide the axles of the truck as long as there is a 3-foot gap between the two vehicles. Such a non-intrusive axle counting solution for ETC systems reduces system maintenance without the need for lane closures.

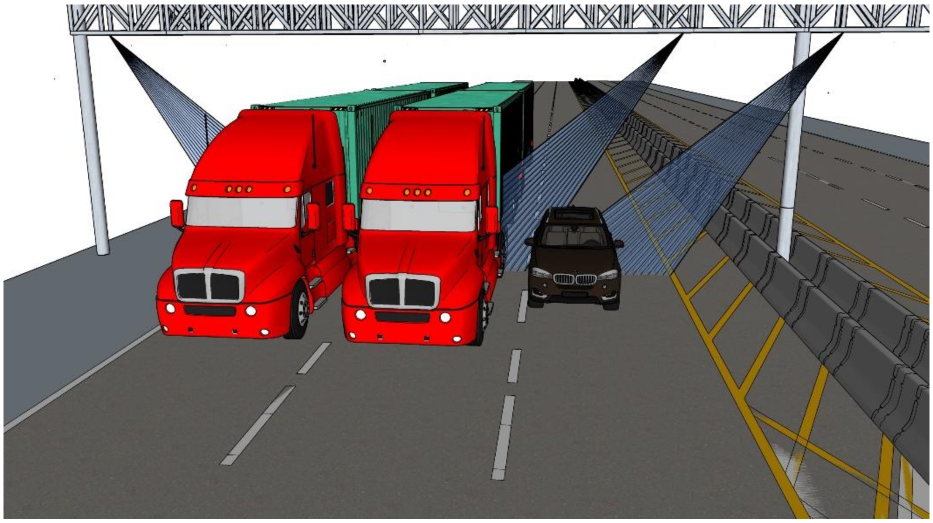


Figure 8 – Sensor mounting enables truck axle counting even in the presence of an overtaking car within the fastest lane

5. Vehicle Classification

Within current ETC systems, two main types of data analysis strategies are currently being used to classify vehicles. The first are classification algorithms which have been written and designed by scientists or engineers. The second is the use and training of neural networks, a branch of artificial intelligence.

For classification systems based on technologies such as ground loops, LIDARs, and radars, the common way to treat the incoming data is with man-made algorithms. Whether by counting the number of axles or by profiling vehicles to obtain their dimensions, or by taking both approaches, it is possible and intuitive enough for professionals to write the necessary algorithms to classify vehicles. For such types of algorithms, though, many situations such as different types of weather or natural conditions or traffic events will require that fine-tuning be done on the algorithms to ensure reliable detection within all these specific situations.

For classification systems based on camera technologies, although it would be very intuitive for a human observer to mentally classify the various types of vehicles that are passing simply by watching the recorded video, creating a classification algorithm using the native data coming from the video captured is a different story. A digital camera only provides values of red, green, and blue for each of its pixels which, when assembled, forms a picture. Interpreting these pixels through algorithms represents a whole new challenge. Hence, companies developing camera-based systems to achieve classification rely increasing on neural network technologies. In a nutshell, the recorded scenes of passing traffic are associated by a human, one by one, to the correct vehicle classification. Once this correlation is established for many thousands of vehicles in many different types of environmental conditions, the data can be utilized to train a neuron network to be able to classify vehicles when provided with new scenes from the tolling camera. The training of these neuron networks is currently contributing to increasing the accuracy of the classification systems, which are driven to the near-100% classification goal.

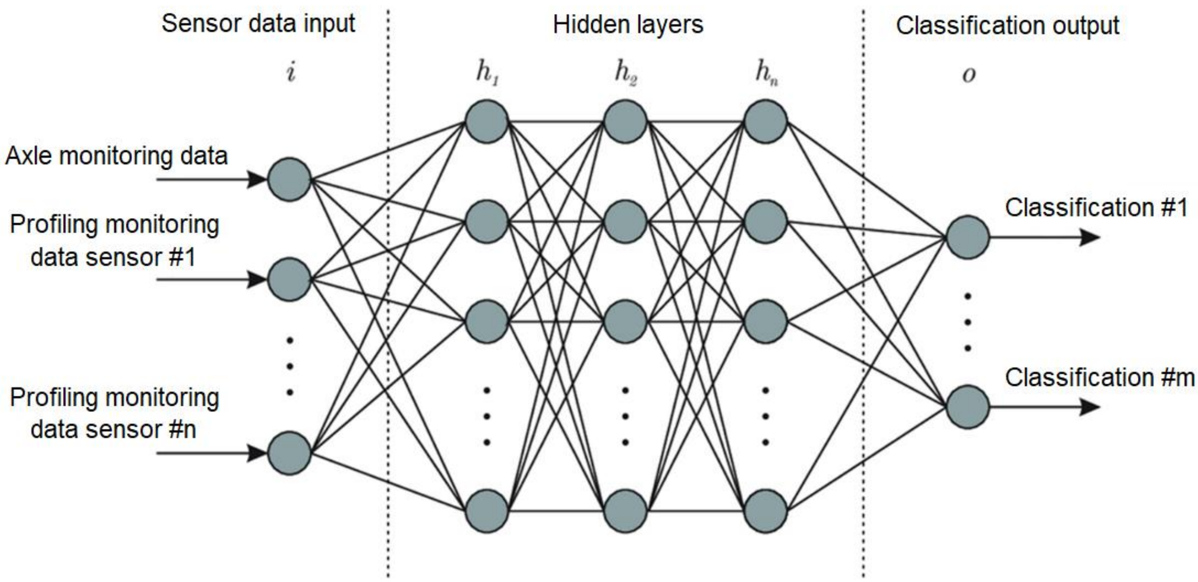


Figure 9 – Basic structure of a neural network using SLL LiDAR data for classification purposes

6. Conclusion

As explained in this White Paper, a new way of non-intrusive axle counting, and vehicle profiling is now possible by leveraging Flash solid-state LiDARs to improve vehicle classification in free-flow tolling systems. Also, new data analysis methods are crossing over from the camera to the LiDAR classification using classification algorithms that are either programmed by engineers or developed through neural network training. These new strategies leveraging Flash SSL sensor technologies are enhancing the ETC system performance, contributing to reducing operating costs while augmenting classification accuracy.

This White Paper does not constitute a reference design. The recommendations contained herein are provided "as is" and do not constitute a guarantee of completeness or correctness.

About LeddarTech

LeddarTech is a leader in environmental sensing solutions for autonomous vehicles and advanced driver assistance systems. Founded in 2007, LeddarTech has evolved to become a comprehensive end-to-end environmental sensing company by enabling customers to solve critical sensing and perception challenges across the entire value chain of the automotive and mobility market segments with its LeddarVision™ sensor-fusion and perception platform. LeddarTech delivers a cost-effective, scalable, and versatile LiDAR development solution to Tier 1-2 automotive system integrators that enables them to develop automotive-grade solid-state LiDARs based on the foundation of the LeddarEngine™. LeddarTech has 14 generations of solid-state LiDARs based on the LeddarEngine™ platform operating 24/7 in harsh environments. This platform is actively deployed in autonomous shuttles, trucks, buses, delivery vehicles, smart cities/factories, and robotaxi applications. The company is responsible for several innovations in cutting-edge automotive and mobility remote-sensing applications, with over 80 patented technologies (granted or pending) enhancing ADAS and autonomous driving capabilities.

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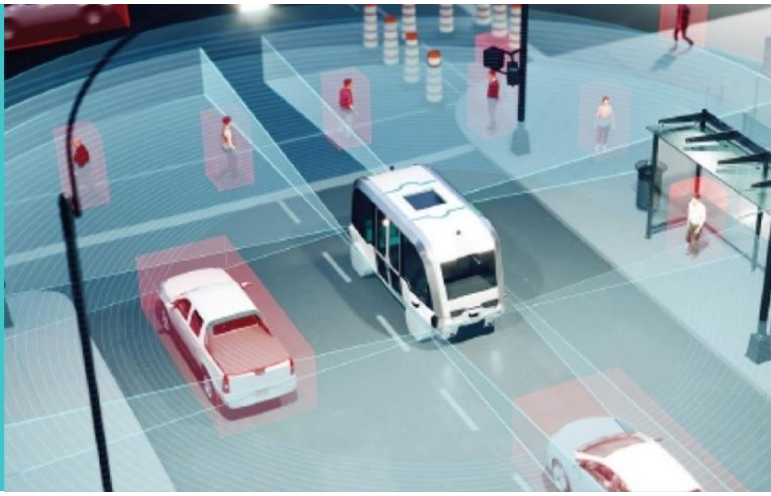

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