SmarTek Systems,™ Inc.

14710 Kogan Drive
Woodbridge, VA 22193
703-680-6554
Sales 410-315-9727

High Performance Multi-Lane Highway Monitoring

Using SAS-1 to "Acoustically Image" the Highway

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Introduction

Highway traffic monitoring has been an ongoing activity for many years for the purposes of road use data collection for required reporting and planning and for real-time traffic management. With growing highway congestion, the need for effective traffic management and traveler information systems has increased dramatically. Effective traffic management and traveler information systems require substantial highway traffic monitoring capability. Highway traffic monitoring capability includes detecting the presence or passage of motor vehicles on a lane by lane basis, and measuring or estimating important parameters such as vehicle count, average speed, and lane occupancy.

The SmarTek Systems Acoustic Sensor -Version 1 (SAS-1) is a novel multi-lane traffic monitoring system based on detecting the acoustic signals motor vehicles create and radiate during operation. The SAS-1 is a non-contact, passive acoustic (listen only) sensor which can provide monitoring for multi-lane highways. It is mounted on existing overhead or roadside structures such as light poles, sign bridges, and overpasses. It is completely non-intrusive to the highway or to the travelers using the highway. The SAS-1 is very compact and lightweight and is designed to be quickly and easily installed on existing highway structures. The SAS-1 is designed to operate from a roadside position. No lane closures are needed for a typical installation on a roadside structure using a bucket truck. Reliability for the adverse highway environment is designed into the SAS-1 to minimize or eliminate any periodic maintenance requirements.

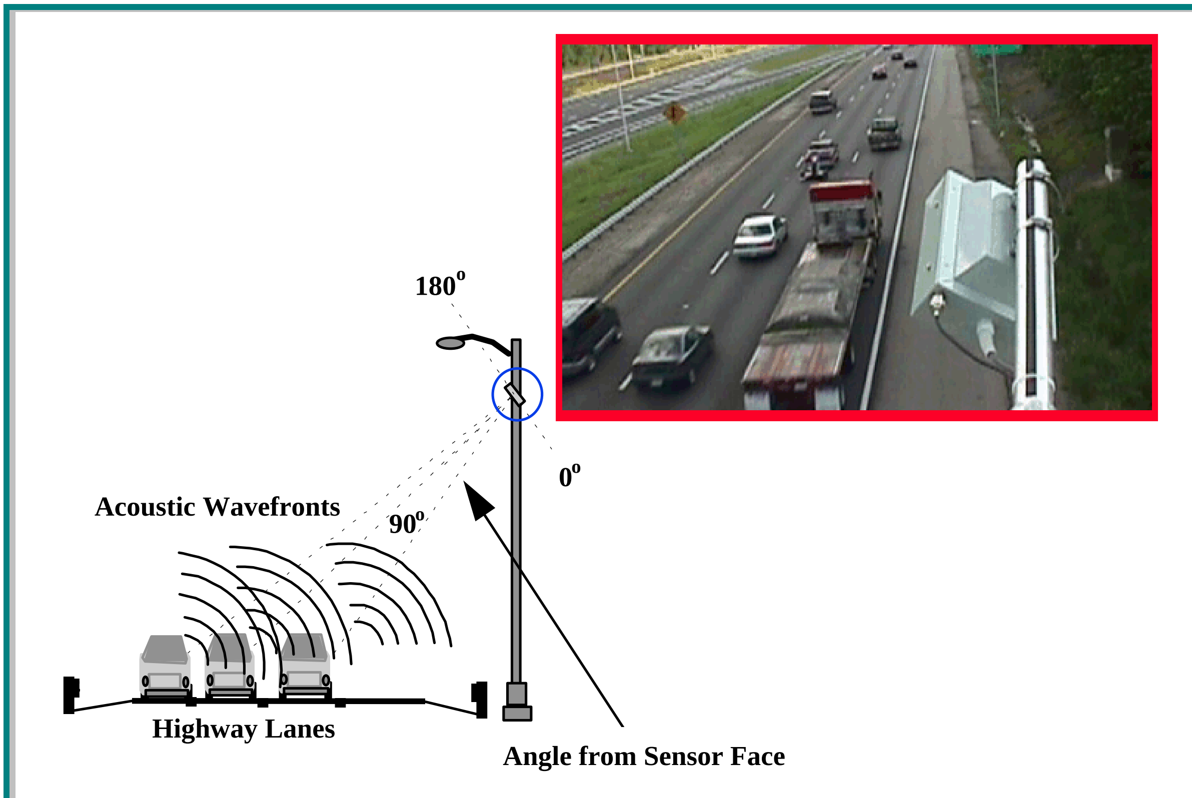

Figure 1 SmarTek Acoustic Sensor (SAS-1)

The SAS-1 is a passive sensor (does not radiate signal) and requires very little power to operate. This coupled with a wireless "home run" option makes the SAS-1 very suitable for completely autonomous installation and operation using a small solar panel to keep an associated battery charged. The need for a hard wired "home run" cable, associated conduit, and installation labor is thus eliminated. Using the SAS-1 with solar power and wireless communication also minimizes weather related project schedule perturbation since there is no need to dig or trench the ground for cables or to cut pavement for loops.

The SAS-1 utilizes SmarTek Systems' advanced signal and spatial processing technology to provide a high resolution "acoustic image" of all vehicle traffic passing by the sensor (including shoulder activity). This advanced processing eliminates false vehicle detections caused by out of lane or off road noise. Because the SAS-1 "acoustically images" the highway traffic with a large number of high resolution cells (or look directions), the end user is provided with significant flexibility to electronically position each detection zone and set each detection zone's size. This capability eliminates the necessity of precise mechanical "pointing" of the sensor to a detection zone position during install. After installation, electronic detection zone positioning and repositioning (if lanes are moved) is accomplished using SmarTek Systems provided Windows based software. The easy to use "SAS Monitor and Setup" software displays the position ("acoustic image") of every vehicle in real time as the vehicle passes the sensor station. Using this display and associated controls, the end user adjusts each detection zone position and size in the cross road direction. This easy process in effect electronically sets each highway lane position relative to the mechanical sensor orientation after the sensor has been permanently "locked down".

How "Acoustic Imaging" Is Accomplished

Consider a group of omni-directional acoustic sensors (microphones) arranged as a closely spaced array in a rigid mounting structure. The microphone array is located off the road at a distance from the highway traffic lanes to be monitored (Figure 1). Acoustic signals (vehicle generated sounds..engine noise, fans, belts, tire noise, etc.) leave their source (vehicle to be detected) and arrive at the array of microphones with an acoustic wavefront which is, for most purposes flat. Each acoustic signal from each vehicle will arrive at the distant microphone array with a different signal level and a different wavefront angle (arrival angle).

The SmarTek Acoustic Sensor-Version 1 (SAS-1) is comprised of an array of rugged microphones, analog signal conditioning, and sampling circuitry for converting impinging acoustic signal wavefronts to digital signals. These digital signals are processed using a programmable state of the art Digital Signal Processor (DSP) with associated memory and communication circuitry. The processing software implements SmarTek Systems' patented advanced signal processing, spatial processing, and vehicle detection algorithms. The SAS-1 "listens to" and processes every received acoustic signal generated by passing vehicles or stationary (idling) vehicles in real time. SAS-1 uses SmarTek Systems advanced signal processing technology to perform signal frequency component discrimination and advanced spatial processing to create multiple acoustic signal arrival direction channels (look directions) as shown in Figure 2. Note that the SAS-1 in one direction implements 91 concurrent listening channels (look directions) and in the other direction a single listening channel.

For multi-lane highway monitoring, the SAS-1 is mounted either roadside or overhead and oriented so that the single listening channel is in the up/down road direction and the 91 listening

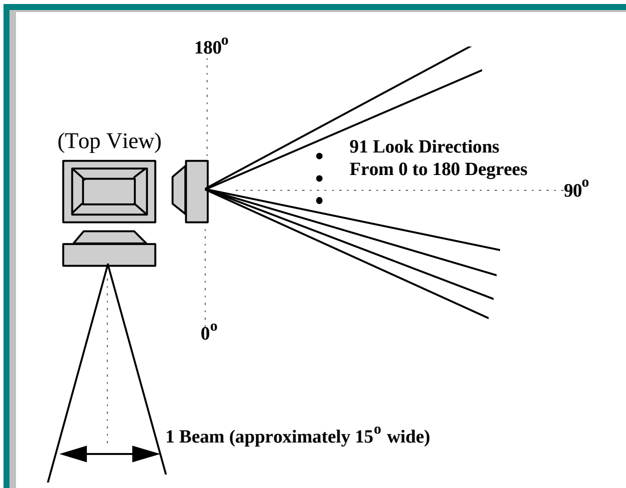

Figure 2 SAS-1 Listening Channels (Look Directions)

channels (look directions) are in the cross road direction as shown in Figure 3. In this configuration, the SAS-1 effectively divides the highway (cross road) into 91 look directions from which vehicle sounds may originate. The single up/down road look direction limits the SAS-1's ability to hear sound in the up/down road direction (only consider vehicle sounds when the vehicle is passing by the sensor station). As vehicle traffic moves or flows by the sensor station, the SAS-1 processing forms acoustic "images" or "blobs" of high signal intensity (multiple adjacent look directions respond to each acoustic signal) as displayed by the SAS Monitor and Setup software running on a laptop PC (Figure 3). Each "blob" represents the acoustic "image" of a vehicle as it passes the SAS-1.

Up to five (5) SAS-1 detection zones are formed by selecting the position and number of contiguous look directions which are combined for actual vehicle detection. This provides the end user with unparalleled flexibility in choosing detection zone sizes and locations. For the example shown in Figure 3, detection zone sizes and placement were selected to correspond to three active lanes and two shoulders. Note that the detection zones (shown by the blue lines) are chosen to leave little or no dead space. That is, where one zone stops, the next one begins. For this configuration, any lane switcher will be detected and placed in one zone (lane) or the other. For the acoustic "image" shown, the blue detection zone indicator lines mimic real highway lane divider lines. The SAS Monitor and Setup display also provides the end user with SAS-1 detection indicator marks (magenta) which are placed in the center of each detection zone. These indicator marks provide the end user with instant feedback to show exactly how well the SAS-1 is detecting vehicles and what zone (or lane) the detections are assigned to. Of course, after setup is complete, the SAS-1 one will operate in flow mode. In this mode, the SAS-1 computes vehicle count, lane occupancy, and average speed for each detection zone (lane) for a specified update period (i.e. 20 sec, 30 sec, 1 minute, etc.). SAS-1 can be set to output these measurements every period or wait to be polled.

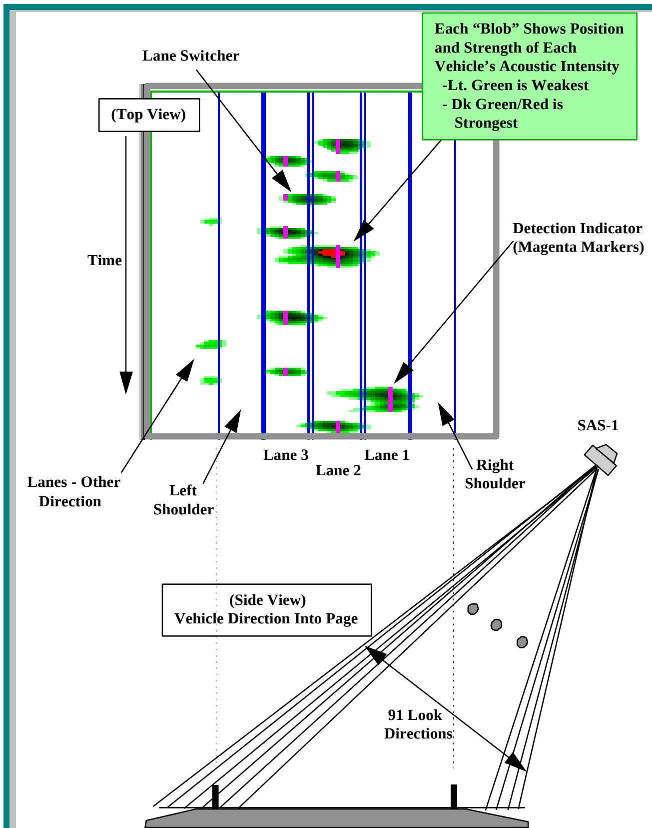

Figure 3 SAS-1 Acoustic "Image" Formation

The SAS-1 is designed to operate and provide effective and accurate true vehicle presence detection and associated traffic flow measures on a lane by lane basis for vehicles passing the sensor station at any reasonable (and allowable) speed from stop and go to free flow. There is no inherent upper speed limitation relative to highway traffic since faster moving vehicles create increased levels of acoustic energy making them easier to detect. The SAS-1 will not tune out a vehicle which remains in the detection zone for a prolonged period of time.

Because the SAS-1 is based on passive acoustic detection of motor vehicles, there is no loss of detection performance due to variation in weather or environmental conditions or visibility conditions.

The number of zones or lanes monitored by the current SAS-1 configuration is set at 5. Figure 4 shows a typical side mount installation geometry for monitoring 3 lanes and 2 shoulders. The detection zone or lane limit of 5 is driven by constraints for a typical side mount geometry (resolution of the far lanes). For an overhead mount geometry, the SAS-1 could perform quite satisfactorily for more than 5 lanes so long as the sensor is centered over the lanes (i.e. 3 or 4 lanes on each side).

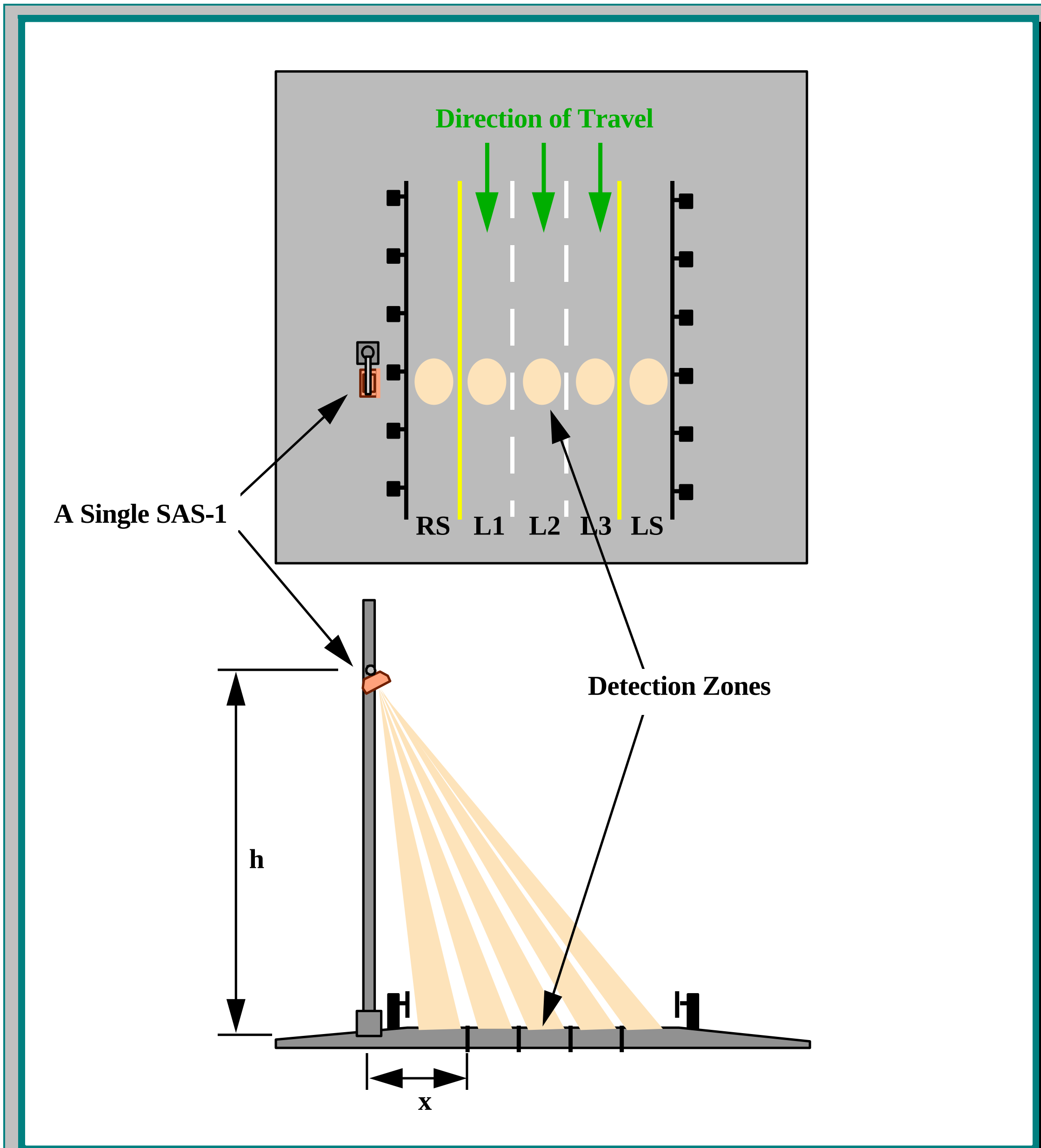

Figure 4 SAS-1 Side Mount Geometry

Performance and Capability

As a more complete example of SAS-1's ability to acoustically "image" the highway, the SAS Monitor and Setup's Real Time Traffic Acoustic Image (TAI) display is shown in Figure 5. The TAI display shows 30 seconds of vehicle acoustic "image" data and detection indicators. The oldest data (passed the sensor earlier) is displayed at the top, while the newest (present time) is at the bottom of the display. This example is from a site monitoring I-95 North bound traffic in Virginia about 25 miles south of Washington DC. The North bound highway configuration consists of three (3) mainline lanes and left and right shoulders. The SAS-1 was placed about 30 feet in height and approximately five (5) feet off of the right shoulder. **The SAS-1 does not need to be mounted over active lanes or over the shoulder (as this example shows).** The time is during the morning rush with heavy in-bound commuter traffic. The major significant point to note is the clearly distinguishable lane by lane clustering and separation of all vehicle acoustic "images" and the resulting SAS-1 detections as indicated by the magenta markers. Traffic flow is rather heavy with the center lane (L2) flow at this time at approximately 30 to 35 vehicles per minute. While these results show excellent lane by lane vehicle detection performance for three lanes and two shoulders, it is clear that SAS-1 can provide excellent performance for five (5) contiguous active lanes using the same roadside installation configuration. Also, as indicated in the display, for this 30 second interval, there are two tractor trailer trucks traveling in the right lane (L1). For the truck which passed the SAS-1 earlier (nearer the top of the display), there is also a very detectable passenger car in the middle lane beside the truck. From the installation geometry, one might expect tall trucks in the right lane to block the sound from cars in the middle lane. The truck in the right lane did not prevent detection of the car in the middle lane as might have been expected. While we do not state that sound occlusion does not occur sometimes, analysis from a significant amount of data indicates that for this typical configuration sound occlusion occurs much less than originally expected.

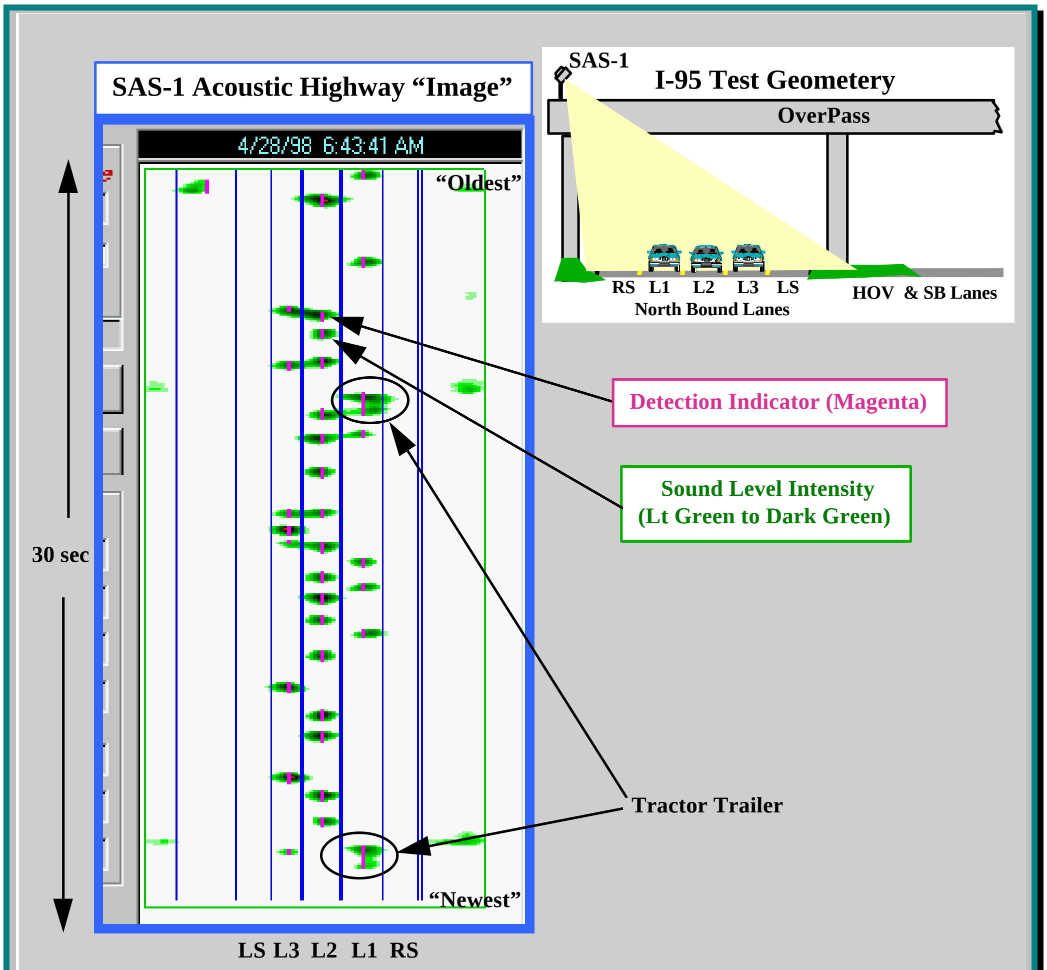

Figure 5 SAS-1 I-95 TAI Display Example

For the two identified tractor trailer trucks, note the distinctive horizontal "V" shape for the acoustic "image". This specific shape occurs consistently for all tractor trailer type trucks. This shape for the acoustic "image" is explainable based on the acoustic source configuration for trucks traveling at speed. The leading edge of the acoustic “image” is the tractor tire noise and engine noise, while the trailing edge of the acoustic “image” is the trailer tire noise. The two edges of the acoustic “image” are connected with the reverberating tire noise reflected from the underside of the trailer. Very preliminary testing indicates that this shape is recognizable at least 90% of the time and may likely be usable for vehicle type identification. Inherent in the processing and detection approach used in the SAS-1 is capability to provide not only excellent vehicle detection performance, but vehicle type identification as well. While vehicles may be treated as single point acoustic sources for detection purposes, they are actually made up multiple, spatially separate, acoustic sources. The tire noise and engine noise within a single vehicle for example, can be resolved and utilized in certain applications. The operational SAS-1 software does not currently provide vehicle type identification.

Figure 6 shows a snapshot comparison between a visual “image” and the corresponding acoustic “image”. Again, this test site is monitoring I-95 North bound lanes south of Washington DC In the figure, groups of vehicles are identified for comparison between the visual “image” and the acoustic “image”. The group of vehicles furthest down road are marked with a cyan ellipse, the middle group with a yellow ellipse, and the group nearest the SAS-1 (just passing) is marked with a red ellipse. As can be seen in Figure 6, the SAS-1 effectively “images” the passing vehicles’ acoustic signals and uses these images to realize high performance traffic monitoring for multi-lane highways.

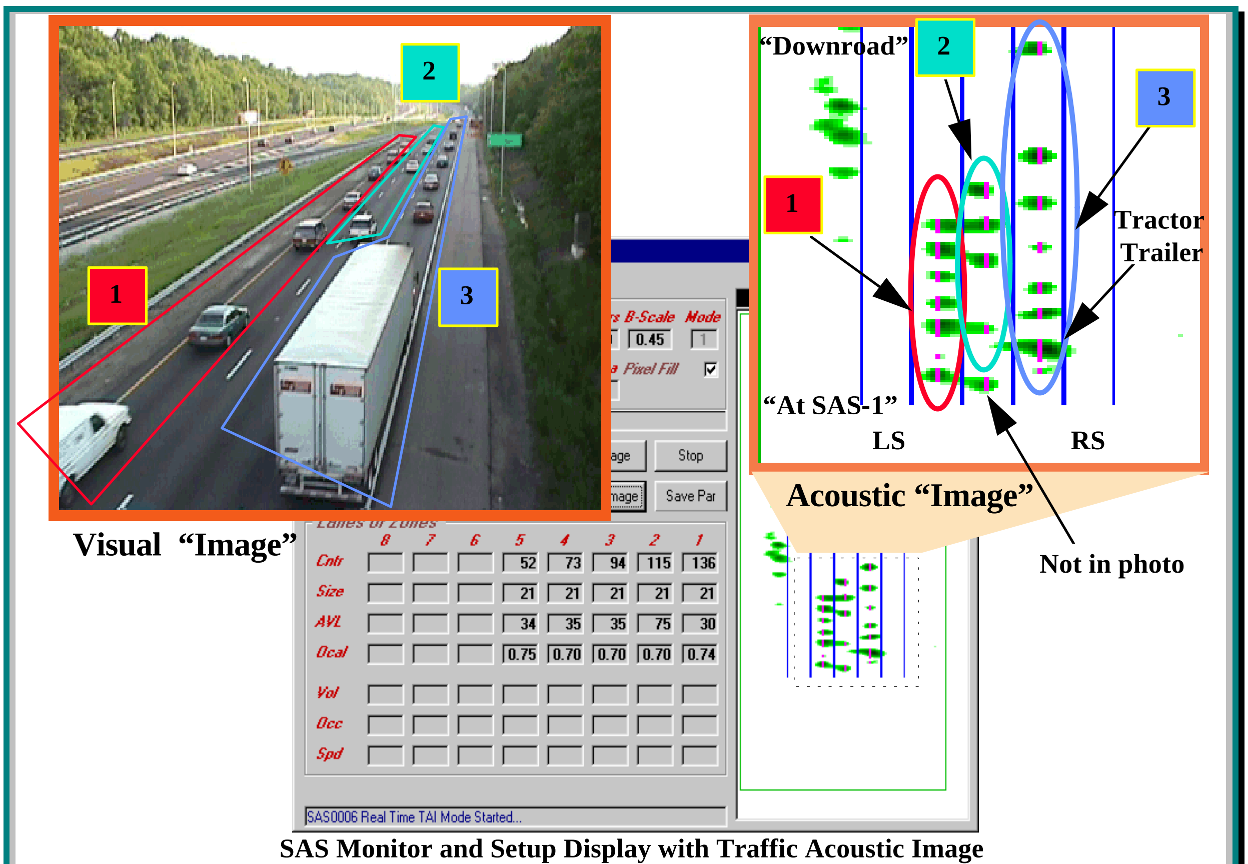

Figure 6 Visual and Acoustic "Image" Comparison

Vehicle Count Comparison

In an effort to completely quantify SAS-1 performance for the roadside installation geometry (Figure 5), vehicle counts from SAS-1 for the Center Lane (L2) were automatically logged to a PC disk file for a 1.5 hr segment and two different 1 hr segments. The vehicle count period was 30 seconds. At the same time, manual visual counts were also collected by human observers from the overpass above the lanes being monitored. For both the manual and SAS-1 counts, synchronization for the 30 second periods was maintained using an audible (head set) alert from the PC at the end of each period (beginning of next period). Of course, there is no way to exactly synchronize the periods and because of this, there are a number of intervals where one or more vehicles were counted in one interval with one counter (human observer) and the adjacent interval with the other counter (SAS-1).

It was decided to concentrate on the center lane (L2) counts in order to collect more extensive data for comparison. We believe that the center lane represents the most challenging lane for accuracy. For the time of day chosen, the center lane vehicle volume was heavier than either the right (L1) or left (L3) lanes. Additionally, most tractor trailer trucks stayed in the right and center lanes, therefore, smaller vehicles in the center lane were more likely to be occluded by large trucks in the right lane. The center lane vehicle count comparison, in our opinion represents a worst case test for SAS-1 accuracy.

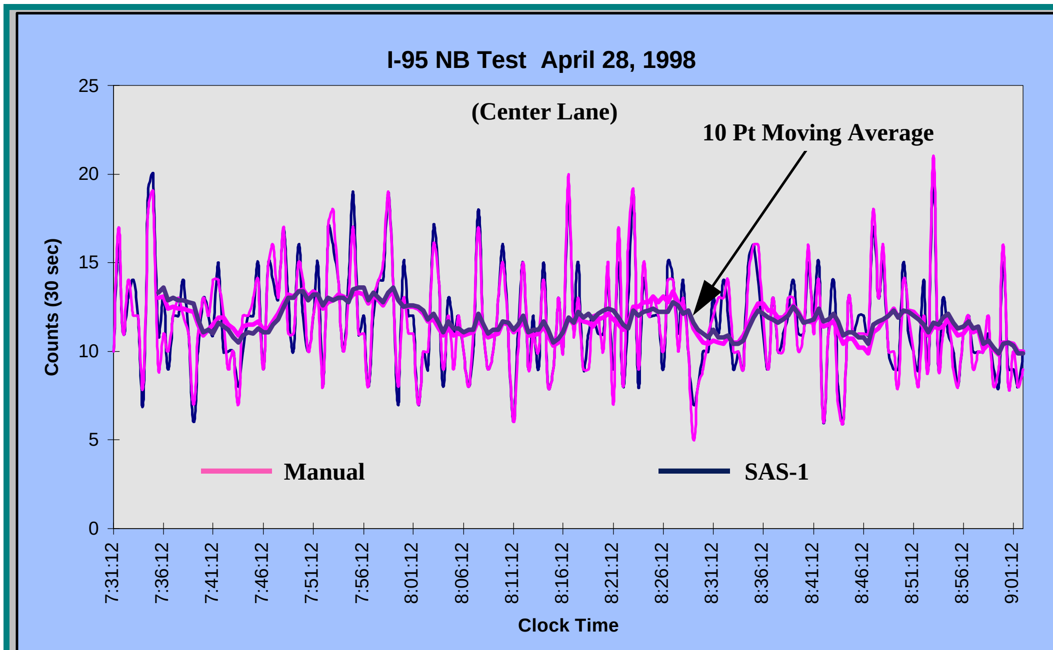

Figure 7 I-95 Northbound Vehicle Count Comparison (Rush Hour)

Consider the comparison results shown in Figure 7. The time period includes 1.5 hours of the inbound morning rush on I-95 south of Washington DC. The plot shows both manual vehicle counts (magenta curves) and the SAS-1 automatic vehicle counts (dark blue curves). The raw 30 second counts and a corresponding 10 point sliding average is shown. Note that for most of this period the traffic volume in the center lane is near 30 vehicles per minute with several instances of nearly 40 vehicles per minute. This traffic volume does represent rather heavy vehicle flow as would be expected for Washington DC area traffic. Most differences observed in the raw 30 second count comparison is due to the placement of vehicle counts in different intervals between the manual and SAS-1 counters A vehicle or vehicles passing the sensor station at the boundary of the 30 second counting interval may be placed in interval “k” by the manual counter (human observer) and interval “k+1” by the SAS-1. This occurs since the intervals are not perfectly synchronized. Note that comparison of the 10 point sliding average shows the two counting results to be virtually the same. In fact, the total count difference for the 1.5 hour period between the manual counts (2141 vehicles) and the SAS-1 counts (2154 vehicles) is only 13 counts. **This difference is only +0.6%.** During this comparison period, some lane switching occurred at the sensor station which caused the human observer to use some judgment when counting (or not counting) a lane switching vehicle.

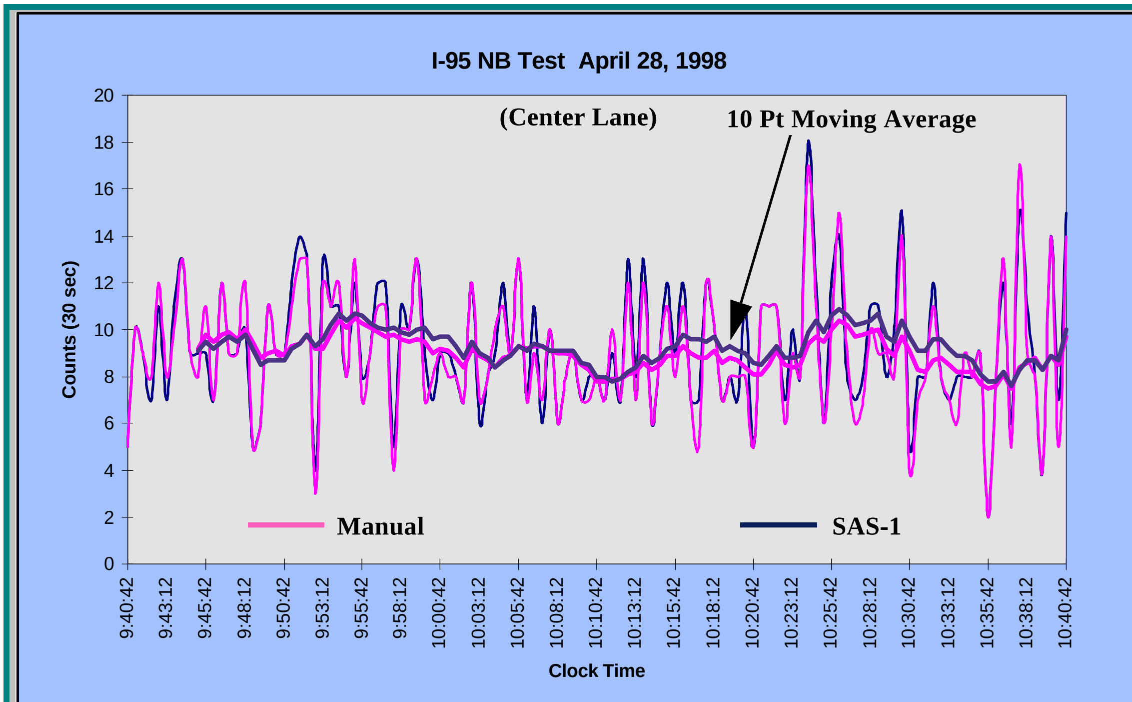

Figure 8 I-95 Northbound Vehicle Count Comparison (Mid AM Rush)

Consider the comparison results shown in Figure 8. The time period includes 1 hour of the later part of the inbound morning rush on I-95 south of Washington DC. The plot shows both manual vehicle counts (magenta curves) and the SAS-1 automatic vehicle counts (dark blue curves). The raw 30 second counts and a corresponding 10 point sliding average is shown. Note that for most of this period the traffic volume in the center lane is near 20 vehicles per minute with several instances of over 30 vehicles per minute. While this traffic volume is lighter than the previously compared period, it still represents rather heavy vehicle flow with a heavier volume of large tractor trailer trucks. Again, most differences observed in the raw 30 second count comparison is due to the placement of vehicle counts in different intervals between the manual and SAS-1 counters. This occurs since the intervals are not perfectly synchronized. Note that comparison of the 10 point sliding average shows the two counting results to agree quite well. The total count difference for this 1 hour period between the manual counts (1091 vehicles) and the SAS-1 counts (1123 vehicles) is only 32 counts. **This difference is only +2.9%.** During this comparison period, lane switching occurred at the sensor station more frequently than the previous period compared. This caused the human observer to use some judgment when counting (or not counting) a lane switching vehicle. The SAS-1 does not appear to miss many (if any) vehicles because of occlusion by large trucks in the right lane.

Consider the comparison results shown in Figure 9. The time period includes 1 hour of a still later part of the inbound morning rush on I-95 south of Washington DC. The plot shows both manual vehicle counts (magenta curves) and the SAS-1 automatic vehicle counts (dark blue curves). The raw 30 second counts and a corresponding 10 point sliding average is shown. Note that for most of this period the traffic volume in the center lane is still near 20 vehicles per minute with several instances of over 30 vehicles per minute. While this traffic volume is slightly lighter than the previously compared period, it still represents rather heavy vehicle flow with a somewhat heavier volume of large tractor trailer trucks. Again, most differences observed in the raw 30 second count comparison is due to the placement of vehicle counts in different intervals between the manual and SAS-1 counters. This occurs since the intervals are not perfectly synchronized. Note that comparison of the 10 point sliding average shows the two counting results to agree quite well with virtually no difference in the latter half of the comparison period. The total count difference for this 1 hour period between the manual counts (1099 vehicles) and the SAS-1 counts (1064 vehicles) is only 35 counts. **This difference is only +3.2%.** During this comparison period, lane switching occurred at the sensor station more frequently than the first period compared. This caused the human observer to use some judgment when counting (or not counting) a lane switching vehicle. The SAS-1 does not appear to miss many (if any) vehicles because of occlusion by large trucks in the right lane.

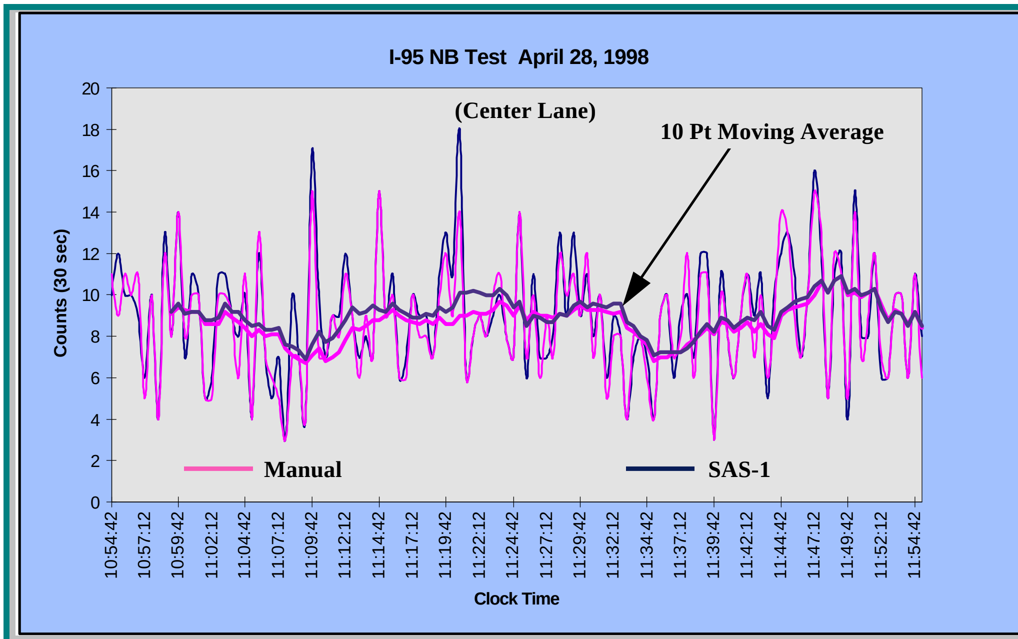

Figure 9 I-95 Northbound Vehicle Count Comparison (Late AM Rush)

Summary

Substantial SAS-1 multi-lane traffic monitoring analysis, including analysis of the data presented in this report shows that high performance multi-lane traffic monitoring is not only possible, but practical and cost effective. Using a side mount geometry for the very compact and lightweight SAS-1 on existing structures can provide multi-lane coverage (up to 5 lanes) without installation (or maintenance) lane closures and in many cases without even shoulder closings. The SAS-1 requires little power and provides a “wireless home run” option which means that when using solar/battery power or taking power from the structure, the home run cable, conduit, routing, trenching, and required installation labor are eliminated. ***Think of it. Cost effective, non-contact, non-intrusive multi-lane traffic monitoring is here!***

Signal Interfaces

The SAS-1 provides for several different interfaces depending on the communication link and the cabinet controller interface desired. The standard SAS-1 output message provides traffic flow measurements of vehicle volume, lane occupancy, and average speed for each monitored zone (up to 5 zones or lanes) for a specified update period (i.e. 20 sec, 30 sec, 1 min, etc). Vehicle presence relays can be provided , however, this option requires a SAS-1 Bit Serial to Parallel Interface in the roadside cabinet. The SAS-1 supports the following electrical communication interfaces:

1) RS-485/RS-422 ....Hard Wired Home Run (up to 1500 feet)
2) RS-232 ....Hard Wired Home Run (up to 100 feet)
3) RS-232 (Optional)..Wireless Link (2.4 GHz Spread Spectrum)

Power

The SAS-1 re-regulates the supply voltage thus compensating for voltage drops and fluctuations caused by long home run cables:

1) Supply Voltage at the Sensor............................7.5 to 24 VDC
2) Required Power.......................................Less than 1.5 watts

Physical

The SAS-1 is a very compact multi-lane highway monitoring sensor. Superior spatial resolution is achieved by advanced processing rather than physical aperture, thereby resulting in a very small sensor footprint (figure 1):

1) Dimensions...................................12 inches long x 8 inches wide x 5 inches deep
2) Weight...Less than 2.5 lb.
3) Material/Finish............................Aluminum/Enamel/Stainless Steel Fasteners
4) Mounting Approach......................2 inch Diameter Aluminum Tube/Stainless Steel Bands
5) Operating Temperature..............-20 Deg C to 75 Deg C
6) Humidity.......................................5% to 100%
7) Shock..NEMA TS2-2.1.10
8)Vibration.......................................NEMA TS2-2.1.9

Installation

The SAS-1 provides a great deal of flexibility relative to installation. Its compact size and modest weight make installation easy for a single installer using a bucket truck. Off the shelf, low cost mounting brackets can be utilized. Mounting brackets should allow for coarse mechanical positioning so that the sensor face is pointing toward the center of the lanes to be monitored (figure 4) with the sensor's long dimension in the up/down road direction and the sensor's short dimension in the cross road direction. Powering the sensor and using the SAS-1 Monitor and Setup program on a PC Laptop makes the SAS-1 installation and pointing easy and quick. Monitoring the real time display while mechanically orienting the sensor removes any guesswork relative to the SAS-1 installation. After the SAS-1 is mechanically oriented and locked down, the position and size of each detection zone (up to 5 in cross road direction) can then be electronically adjusted using the SAS-1 Monitor and Setup program to precisely match the highway lanes and the specific traffic flow situation.

1) Height Above Pavement.......................................20 to 40 feet
2) Horizontal Distance to First Detection Zone..........0 to 40 feet
3) Coarse SAS-1 Orientation..................Mechanical with SAS-1 Monitor and Setup Software
4) Precise Detection Zone Adjustment.......Electronic with SAS-1 Monitor and Setup Software