Review, Experimental Evaluation and Policy Considerations of a Directional Time of Day Truck Restriction on Highways

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The paper reviews several strategies of restricting or separating trucks from the regular traffic stream. Typical truck restriction policies focus on leftmost lanes restriction, which has been shown by several studies to have some advantages. However, those studies clearly show that vehicle queue lengths in the vicinity of critical merging areas increase significantly as the percentage of trucks increases. Therefore, this study examines a different policy—one which investigates traffic efficiency gained by restricting heavy truck traffic in one direction—in this case, westbound on Highway 1 in Israel—during afternoon peak hours. Similar policies of utilizing a specific vehicle category (e.g. passenger cars or trucks) in different daily time periods or physical separation of homogenous traffic of passenger cars in the inner lanes and mixed traffic in the outer lanes, were recommended in Italian motorways and in New Jersey Turnpike dual-dual freeways respectively.

Highway 1 is a freeway connecting Jerusalem and Tel Aviv that passes by Ben-Gurion International Airport. The major objective of this study is to estimate the benefit of restricting truck traffic in the traffic stream according to three traffic-flow parameters: average travel time, total travel time, and average traffic speed. Analysis of the results, which consider the significant differences of 30-minute time period samples ("before-after" truck restriction), shows that prohibiting trucks in all lanes in one direction during the peak afternoon period of 16:00-18:00 improved all three traffic flow parameters by 8%-12%. Generally a steep grade from which truck traffic is banned is correlated with an improvement in traffic flow. In our case, Highway 1 road segments 1 and 2 and 4, which have steep grades (longitudinal grades), incorporated the most significant improvements in the traffic stream parameters examined.

INTRODUCTION

The large presence of trucks (especially slow trucks) on interurban highways increases the variability of the traffic flow, because of the differences in operational characteristics between the heavy vehicles and passenger cars. Trucks have a lower capability to accelerate or to harmonize with the speed of the general traffic, particularly on steep and continuous grades in the road profile (longitudinal grades). Therefore, trucks may cause the formation of long queues; merging, diverging (Siuhi and Mussa 2007, El Tantawy et al. 2009), and weaving difficulties; and a deterioration in both traffic flow quality and traffic capacity.

As far as safety is concerned, the presence of trucks in the traffic stream reduces sight distance while the travel changes direction (therefore it requires driving along curves) and while the steepness of grade changes its magnitude and trend (either from upgrade to downgrade or from moderate grade to steeper grade and vice versa). Such driving maneuvers have to be taken into account in the design of horizontal and vertical curves along the highway alignment correspondingly, as clarified in Appendix A. Sight distance reduction (by the presence of trucks in the traffic stream) might hide the viewing of traffic and message signs as well.

When passenger car drivers want to pass wider trucks, they might position themselves too close to the pavement edge and so reduce the margin of safety. Furthermore, trucks traveling at high speed create significant air disturbances, which can cause unsuspecting motorists to lose control of their cars. Large trucks also exert psychological effects. Passenger car drivers often feel threatened by the closeness of trucks in an adjacent lane, since the large vehicles occupy more length and lane width than does a passenger car.

Implementing truck restrictions may enhance the efficiency of highway travel through reducing the travel times of regular traffic and improving safety; however, trucking companies have expressed concern over such steps, since such restrictions can negatively impact trucks' travel times and change their travel routes and scheduling. Therefore, the profitability and efficiency of these trucking companies might diminish. Deterioration in profitability and efficiency of trucking companies by denying access to trucks also impacts the economic efficiency of industries and variety of producers.

This study focuses on an investigation of traffic efficiency when heavy truck traffic is restricted. The case study for this investigation was Highway 1 in Israel during afternoon peak hours. Route 1 is a major highway that connects the cities of Jerusalem and Tel Aviv and passes through the Ben-Gurion International Airport interchange. The highway section examined transfers of nearly 3,000 vehicles per hour in each direction exiting/entering Jerusalem; about 5% of this traffic comprises trucks (approximately 150 trucks per hour in each direction). This section starts at the Sakharov Gardens intersection (exiting Jerusalem) and ends at the Daniel Interchange (providing a merger to a freeway, Route 6). The section terrain is partially hilly and includes several horizontal and vertical curves. Its length is 34 kilometers. Heavy traffic conditions characterize the morning peak when driving eastward to enter Jerusalem and the afternoon peak hours when driving westward exiting Jerusalem. Delays are principally caused by heavy traffic, exacerbated by trucks slowing considerably on the upgrades of the hilly topography. Since there is no climbing lane, the regular traffic needs to perform a passing maneuver along the left lane, in effect leaving only one lane for the regular traffic stream when a slowing truck approaches the traffic stream. The major objective of this study is to estimate the benefits of restricting truck traffic on this section during the peak hours.

Research Motivation

Although a large amount of travel time and speed analyses (literature review section) had indicated that the left-most lanes from which trucks are restricted have some advantage compared to non-restricted lanes, the potential of vehicle queue length in the vicinity of critical merging areas increases significantly as the percentage of trucks increases. This phenomenon is associated with the unavailability of acceptable gaps for merging onto the freeway during peak traffic conditions and, consequently, with vehicular conflicts and the possibility of traffic crashes. This correlation and hardly any previous empirical and experimental studies of time of day truck restriction lead to the present study of prohibiting trucks from all lanes during peak hours.

The advantage of the procedure proposed in the current study is the analysis of average travel time and average speed parameters of a specific segment by direct measurements compared to the need for several steps to obtain these parameters according to HCM procedure.

LITERATURE REVIEW

In Germany, most trucks are limited to 80 or mostly 90 per km/hour (50 and 56 mph, respectively) on the "Autobahn" or freeway (expressway). The speed limit for cars and motorcycles is much higher: 130 km/hour (or 81 mph). This difference in speed limit between heavy vehicles and passenger cars is acceptable in European Union countries. The fact that traffic laws in Europe enforce drivers to keep driving on the right lane, excluding overtaking maneuvers, and that many expressways of the European highway network consist of two lanes per direction, lead to the practical outcome of restricting truck traffic to the right lane even though heavy vehicles are officially informed to drive on the right lane (McCarthy 2005).

Most of the traffic studies regarding the benefits of truck restrictions were performed in the United States. In general, trucks are restricted to using the rightmost lane or lanes of freeways because the left lanes are regarded as passing lanes. Nonetheless, there are some situations in which trucks are restricted from using the right lanes instead of the left lane because of safety problems presented by merging and diverging traffic (Hoel and Peek 1999).

The major motivation of implementing lane restriction for trucks is improving traffic operation. Other incentives of implementing lane restriction for trucks are reducing vehicle crashes and limiting pavement damage (Yang and Regan 2013).

Prohibiting trucks from using certain lanes on multi-lane highways gives other vehicles the opportunity to enter the traffic stream and, avoiding the interference of heavy trucks, to reach a higher travel speed on the otherwise restricted lanes. This effect might improve the quality of traffic stream and increase a highway's capacity.

Strategies of Separating Cars from Trucks

Ferrari (2009, 2011) proposed a model of competition between cars and trucks on Italian motorways' sections when the willingness to use the motorway of both cars and trucks increased but the geometric characteristics remained unchanged. The fact that weekends and holidays are associated with almost only passenger car travel (one vehicle category) and weekdays include traveling by both categories and a progressive increase of truck traffic on motorways might suggest that motorways should be used by a specific vehicle category (e.g., one category: passenger cars or trucks) in different daily time periods (Ferrai 2009, 2011). Moreover, the strategy of separating cars and trucks on the New Jersey Turnpike dual-dual freeway also resulted in a safety improvement based on Lord et al. (2005).

Time-of-day restrictions are applied to prevent trucks from using a lane or a road during high-level traffic congestion. Some U.S. states restrict trucks from using a freeway in order to reduce peak traffic and increase travel speeds (Mussa 2004). Stokes and McCasland (1986) stated that truck traffic volume does not tend to peak during the regular morning and afternoon commuter peaks. Therefore, truck restriction during the regular driving peak hours could produce only subsidiary improvement in freeway traffic operations. Another interpretation is that prohibiting trucks during the peak hours of high travel demand might bring additional daily traffic to the traffic stream, causing operational improvement to the traffic flow to be marginal. Grenzeback et al. (1990) similarly found that the volume of large trucks on urban freeways does not have a crucial effect on the traffic stream during peak congestion hours unless either the percentage of truck traffic exceeds 10% or the congestion is accompanied by a truck incident, particularly a "truck-involved" accident.

Flow, Speed, Travel Time and Traffic Operations Studies

Jo et al. (2003) used VISSIM simulation software to assess the impact of prohibiting trucks from using the leftmost lanes on highways with 3-5 lanes in each direction. The study found that Truck Lane Restriction (TLR) increased throughput only when the restricted number of lanes was limited and the percentage of trucks was lower than 25%. The average speed increased under such conditions. The average speed was reduced, however, under high truck percentages and an increased number of restricted lanes; ramp volume and interchange density in this case had a negative effect on speed. The researchers recommended restricting trucks from the two leftmost lanes for rural area highways with 4-5 lanes in each direction and from the leftmost lane when there were three lanes in each direction. They recommended that truck lane restrictions should not be applied in urban areas, where capacity was critical.

Moses et al. (2007) simulated traffic flow of Interstate 95 in southern Florida They found that the restrictions of the right and center lanes caused traffic flow disruptions owing to the queues that developed upstream of interchanges during the peak hours; i.e., the formation of excessive queues as entering trucks waited long periods for a gap in order to move from the restricted lanes. Yang and Regan (2013) examined three truck traffic strategies for Interstate 710 (23-mile corridor in California): 1) no strategy for trucks, 2) trucks' restriction from one leftmost lane, and 3) trucks' restriction from two leftmost lanes. The analysis period was midday peak time (i.e., time of day) while traffic flow ranged between 970 and 1,950 vehicle/hour/lane with 13% trucks (annual basis).

A simulation analysis of 60 minutes resulted in minor improvement of traffic delay (minute per vehicle) along the corridor: 11.88 minutes per vehicle for strategy 1 (existing situation), 11.79 for strategy 2 (one leftmost lane restricted), and 11.55 for strategy 3 (two leftmost lanes restricted). This measure of effectiveness, which represented traffic congestion, decreased by only 2.8% if strategy 3 was implemented (Yang and Regan 2013). These results imply that in order to significantly improve traffic congestion it might be more reasonable to implement a directional time of day truck restriction strategy as proposed in the current study.

Siuhi and Mussa (2007) found that during peak hours, HOV lanes and car lanes experienced better travel times than did the lanes that permitted truck traffic. The leftmost lanes (including HOV lanes, which were restricted from trucks) had higher speeds than unrestricted lanes. They interpreted this by the fact that congestion on the right lanes ("queue length in the vicinity of critical merging and diverging areas") forces passenger cars to use the left lanes and concluded that restriction of HOV lanes and left lanes in urban freeways improves traffic operation and traffic safety during congested conditions rather than during non-peak traffic conditions. However, Mussa (2004) has shown that regardless of the time of day, no significant difference in travel time and travel delay occurred between restricted and unrestricted conditions (on Interstate 75, Florida).

Qi et al. (2009) investigated the restriction of trucks to the right lane of four-lane rural freeway (elevated I10, Louisiana) with a speed limit policy of 55 mph. Their statistical analysis indicated that the speed in the left lane was much higher than the speed in the right lane.

El-Tantawy et al. (2009) found that restricting the two leftmost lanes from trucks in Gardiner expressway (downtown Toronto) caused an increase in truck-related merging conflicts along the right lane.

Grade Effect

Using Remote Traffic Microwave Sensors (RTMS) technology to collect real traffic data, Cate and Urbanik (2004) investigated the impact of left-lane restriction in Knoxville, Tennessee (Interstates 40, 75). The scenarios were run for three lanes in each direction, with and without ramps. In order to quantify the effect of lane restriction, they conducted a before-and-after study. Travel time estimations showed that with an increased grade (4%), a left-lane truck prohibition resulted in saving travel time for PCs (passenger cars) and in slightly increasing travel time for trucks. However, the travel time savings for passenger cars on level terrain was minimal. Specifically, the speed differential between trucks and PCs was less than 1.0 mph on level terrain and approximately 10.0 mph on 4% upgrades. Furthermore, the average travel times for cars traveling a five-mile stretch along a freeway segment with a 4% uphill grade was reduced by approximately 60 seconds (Cate and Urbanik 2004).

Based on several literature sources, the overall impact of a left-lane restriction for trucks (or a limited number of restricting lanes from the left, e.g., two left lanes restricted out of for four or more lanes per direction) and directing the truck traffic to the rightmost lane moderately reduces the travel time of passenger cars in the restricted lanes where trucks are prohibited. However, some other studies might argue with this statement by either suggesting a physical separation between homogenous traffic of light vehicles and mixed traffic, and diverting trucks to alternative routes, or prohibiting trucks from the rightmost lanes to avoid merging and diverging impedance. Safety studies basically document reduction in crashes while prohibiting trucks from the left lane or physically separating the passenger car only lanes.

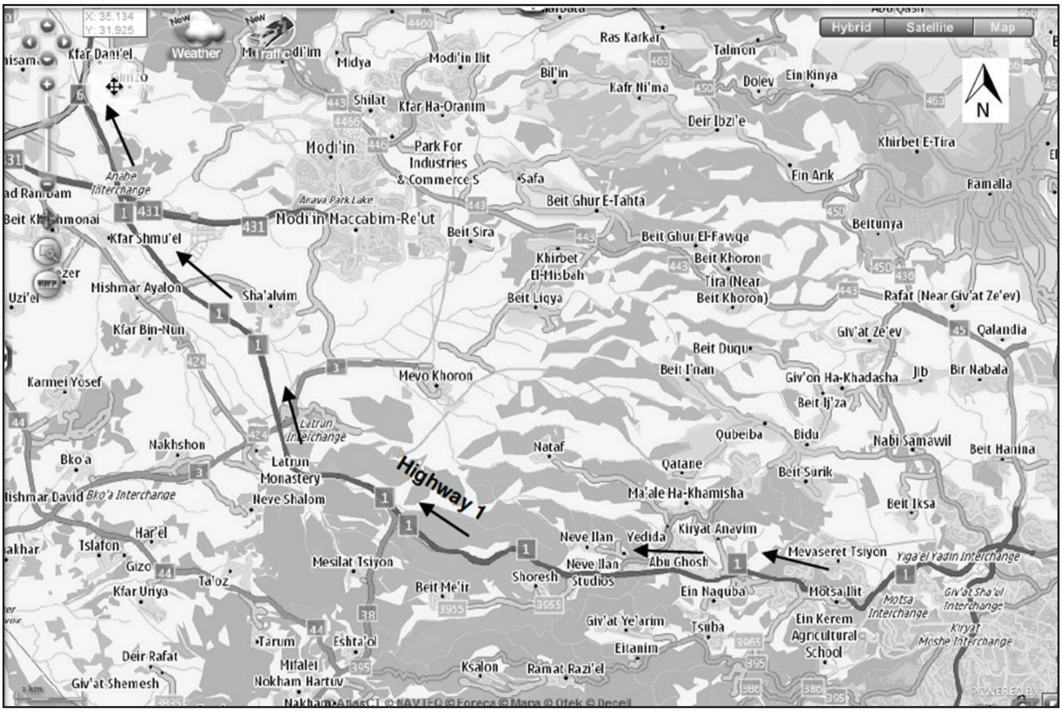
DATA FOR ANALYSIS AND PILOT STUDY DESCRIPTION

The pilot study examined traffic flow parameters before and after truck restrictions, based on two sets of measurements. The first data set was generated before the prohibition. The second data set was measured two months after applying the truck prohibition (beginning of March 2011) in order to maintain a "learning" period for the drivers to become accustomed to the new traffic regulations.

The data used for the analysis were obtained by restricting trucks in the westbound direction of Highway 1 during the peak afternoon hours, 16:00-18:00 (4-6 pm).

A traffic sign arrangement plan was implemented by posting signs announcing the prohibition of heavy trucks (above 12 tons) before the restricted segments and along the interchange ramps and the adjacent roads leading to these segments. Messages were also reported in the media in order to allow drivers and trucking companies to plan truck routes accordingly. During the pilot study, the police increased its enforcement along and prior to the prohibited zones. The restricted section along Highway 1 is presented in Figure 1.

Figure 1: Restricted Sections for Trucks Along Highway 1 Westbound from the Jerusalem Exit (from Sakharov Gardens Intersection – Daniel Interchange)



METHODOLOGY

The success of implementing the truck prohibition was evaluated by three traffic parameters:

(1) Average travel time (ATT); it was hypothesized that truck ATT would decrease by 5% or more compared with the ATT before the truck prohibition. The ATT for one subsection (ATT_k) is calculated as follows:

$$(1)\quad ATT_{k,j} = \left(\frac{\sum_{i=1}^{4}(Vol_{i,j} \bullet TT_{i,j})}{\sum_{i=1}^{4}(Vol_{i,j})}\right)$$

$$(2)\quad VOL_{k,j} = \sum_{i=1}^{4}(Vol_{i,j})$$

(3) $$ATT_k = \left(\frac{\sum_{j=1}^{3}(ATT_{k,j} \bullet VOL_{k,j})}{\sum_{i=1}^{3}(Vol_{k,j})}\right)$$

Where:

Vol_{ij} – traffic volume of one vehicle type (j) measured for half an hour (i) during the truck restriction period (16:00-18:00).

TT_{ij} – travel time of one vehicle type measured for half an hour during the truck restriction period (16:00-18:00)

i – 30-minute period sequence number during the afternoon peak hours (16:00-18:00), i.e. i=1 for the period 16:00-16:30, i=2 for the period 16:30-17:00, and so forth.

j – vehicle type (1 for light vehicles, 2 for medium vehicles, 3 for heavy vehicles)

k – segment (subsection) number

The ATT is calculated by summing up the ATT_k for all segments.

(2) The total travel time (TTT) after the truck prohibition was hypothesized to decrease by 5% or more than the TTT before the truck prohibition. The TTT is calculated by adding the product of the average travel time to the traffic volume of all traffic streams in each direction.

The TTT for one subsection (TTT_k) is calculated as follows:

(4) $$TTT_k = \sum_{j=1}^{3}\sum_{i=1}^{4}(Vol_{i,j} \bullet TT_{i,j})$$

The definitions of Vol_{ij}, TT_{ij}, j, and k are identical to the ATT_k equation. The TTT is calculated by summing up the TTT_k of all subsections.

ATT and TTT were calculated for the two-hour restriction period (16:00-18:00) before the truck restriction and after the restriction.

(3) The average speed (S) during the peak hour (16:30-17:30) of the restriction period was hypothesized to increase by 5% or more compared with the average speed before the truck prohibition. The average speed for one subsection (S_k) is as follows:

(5) $$S_k = \frac{L_k}{ATT_k} \; ,$$

Where:

ATT_K – calculated sum for two periods of 30 minutes each (during the peak hour period; i.e., a one-hour restriction period). Mathematically the summation is performed for i=2,3 in equations 1 and 2.

L_k – length of subsection k

The computed average speed for the whole section (S) is proportional to the length of the segment (L_k):

(6) $$S = \frac{\sum_{k=1}^{8} S_k \bullet L_k}{\sum_{k=1}^{8} L_k}$$

Data for Analysis

Traffic counts and travel time measurements were collected during weekdays. The first data set before the prohibition of truck travel was measured on December 28, 2010. The second set (after the prohibition was applied) was measured on March 1, 2011. Both days of measurement are considered typical working days in Israel (no vacation and regular school days).

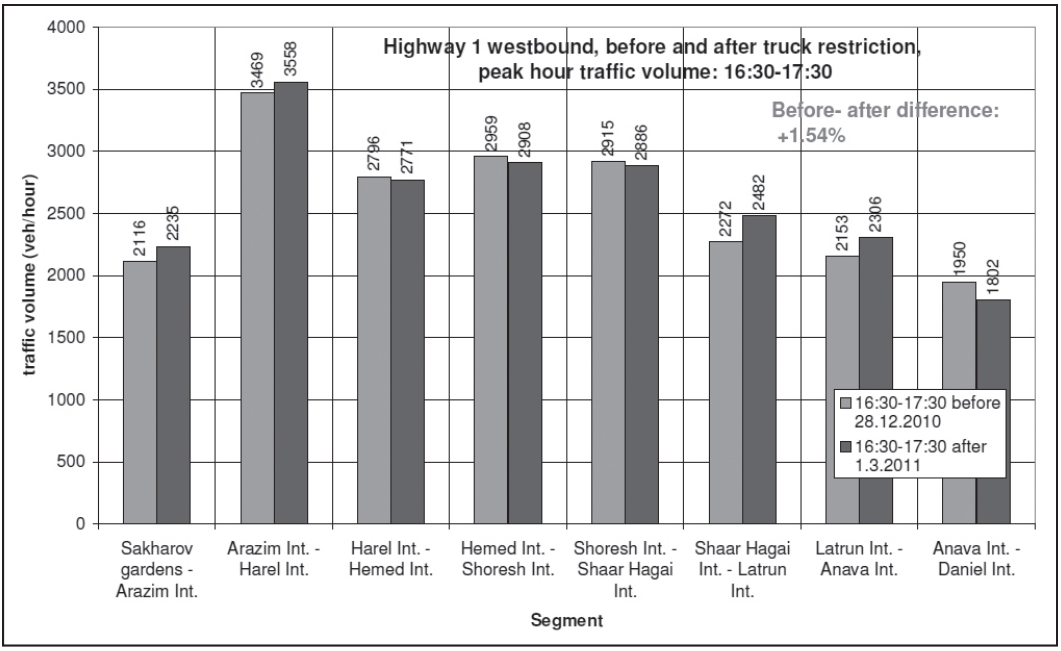
Division into Subsections. The entire study section along Highway 1 from the Jerusalem exit (Sakharov Gardens Intersection) to Highway 6 (Daniel Interchange) was divided into eight segments, based on ramp locations. Traffic flow parameters were measured on each segment. The partition points along the study section were at nine interchanges: Arazim, Harel, Hemed, Shoresh, Shaar Hagai, Latrun, Anava, and Daniel.

Vehicle Type. Three vehicle types were considered: light, medium, and heavy vehicles, with light vehicles corresponding to passenger cars, and medium vehicles to trucks with one rear axle. The medium vehicle type (mostly single unit trucks) could weigh either less or more than 12 tons. Heavy vehicles corresponded to buses, trucks with at least two rear axles, semi-trailers, and full trailers. Specific heavy trucks weighing more than 12 tons, which are considered vital by Israel's Ministry of Transport (e.g., trucks transporting basic food products, garbage trucks), received permission to drive along the prohibited routes. Buses, which are included in the heavy-vehicle category and are considered vital to the transportation system during the peak period, were not regarded as prohibited vehicles.

Traffic Counts. The raw data were collected by real-time video photography. Automatic vehicle counters were also used for backup and validation of the video traffic volume data.

Traffic counts were processed for each subsection for time periods of 30 minutes during the afternoon peak hours. Figure 2 presents a histogram of traffic volumes for the peak hour (16:30-17:30) before and after the truck-restriction period.

Figure 2: Traffic Volumes for Peak Hour (16:30-17:30) Before and After Truck Restriction



The volume of light vehicles increased by 2.35%, and the medium plus heavy vehicles decreased by 9.1%. The total number of vehicles increased by 1.54%. It appears, then, that the truck prohibition affected passenger car travels during the afternoon peak hour positively, but only slightly.

Travel Time Measurements. Travel times were measured from the raw data of the video recording of each segment by processing approximately 30 vehicles each half hour after the raw data results of the video recording of each segment were processed. Vehicle characteristics (light, medium, or heavy) were identified at the beginning and at the end of the segment in order to measure the travel time of each vehicle type that passed along the segment. The selection of vehicles for identification was random and approximately balanced between vehicle types in order to reflect all vehicle types in the traffic stream and preclude a bias in the estimated averages. The travel time was averaged according to vehicle type and each 30-minute period.

DATA ANALYSIS AND RESULTS

Before-After Statistical Analysis of Travel Time Measurements

Each sample of the before-and-after truck prohibition included the travel time (TT) segment measurements for one vehicle type (light, medium, or heavy). Two sample t-tests were made to examine whether the difference in the TT means (ATT) between the two samples (before and after the prohibition) was significant. The test assumed that the sample size was small ($n \leq 30$) and the standard deviations of the two populations were unequal (Satterhwaite's approximation, 1946). The H_0 and H_A hypothesis definitions are as follows:

H_0 (Null hypothesis): The means of two samples are not significantly different from each other.

H_A: The means of two samples are significantly different from each other (two-tailed t- test).

If the difference is not significant at the 5% significance level (95% confidence level), the ATT (average travel time) before and after the truck prohibition would be assumed to be identical (not significantly different) and computed as the "before and after" average travel time.

The equations required for testing the significance of the two samples are as follows:

(7) $$t(actual) = \frac{ATT_a - ATT_b}{\sqrt{(\frac{s_a^2}{n_a} + \frac{s_b^2}{n_b})}}$$

(8) $$d.f. = \frac{(\frac{s_a^2}{n_a} + \frac{s_b^2}{n_b})^2}{\frac{\left(\frac{s_a^2}{n_a}\right)^2}{n_a - 1} + \frac{\left(\frac{s_b^2}{n_b}\right)^2}{n_b - 1}}$$

Where:

s_a^2 – an estimate of the population variance (sample variance) after the truck prohibition (light, medium, or heavy vehicle) for a 30-minute time period

s_b^2 – an estimate of the population variance (sample variance) before the truck prohibition (light, medium, or heavy vehicle) for a 30-minute time period

n_a – sample size after the truck prohibition (light, medium, or heavy vehicle) at 30-minute time intervals

n_b – sample size before the truck prohibition (light, medium, or heavy vehicle) at 30-minute time intervals.

ATTa – sample mean after truck prohibition

ATTb – sample mean before truck prohibition

t(actual) – testing parameter: reject the null hypothesis ($ATT_a – ATT_b = 0$) if t(actual) exceeds $t_{0.05/2}$ or is less than - $t_{0.05/2}$

d.f. – calculated degrees of freedom, assuming unequal variances, based on the Welch–Satterthwaite approximation (Satterthwaite 1946, Welch 1947).

If t(actual) > $t_{0.05/2}$ (i.e., p-value ≤ 0.05), there is significant statistical evidence in support of rejecting the null hypothesis. In other words, the means of the two samples are significantly different. There is, in that event, no more than a 5% probability that we could obtain this result by chance (an acceptable level of error).

Typical Travel Time "Before-After" Analysis Examples for the Arazim Harel Segment

Table 1 presents a "before-after" analysis of two 30-minute periods during the afternoon peak hours on the Arazim Interchange–Harel Interchange road segment: 17:00-17:30. Table 2 summarizes the t-test travel time results for the whole afternoon peak period (16:00-18:00) for the Arazim–Harel segment, based on four samples of 30-minute time periods (16:00-16:30, 16:30-17:00, 17:00-17:30, and 17:30-18:00) and vehicle type (light, medium, and heavy).

Sample Size Verification of Travel Time Measurements

The minimum required sample size of travel time observations for a certain vehicle type before or after truck prohibition (for a specific 30-minute time period) can be computed by the following formula.

(9) $$n \geq \frac{t^2_{1-\frac{d}{2},n-1} \times C^2}{D^2}$$

where,

$t_{1-\frac{d}{2},n-1}$ Student distribution with (1-d)*100% confidence level and n-1 degrees of freedom.

C – Sample Coefficient of Variance (ratio of the sample Standard Deviation to the mean).

n – the required number of travel time observations for a specific vehicle type during the defined time period.

D – precision interval as a proportion of the mean (%).

This formula helps "to estimate the minimum sample size needed to achieve any desired precision intervals or confidence levels" (Traffic Monitoring Guide 2013).

The TMG (2013) recommends the integration of a confidence level of 95% and precision intervals of ±10% for traffic engineering purposes in order to determine sample size requirement. The typical sample size results presented in Table 1 (Arazim-Harel Interchange, 17:00-17:30) show that the precision level does not exceed 10% except the heavy vehicle travel time observations after truck prohibition, which resulted in D= ±11.2%. A possible clarification for the slight deviation in precision level is that the heavy vehicle type of this typical time period and road segment might have been less homogeneous in terms of gross weight and vehicle performance characteristics.

Summary of Data Analysis Results: Average Travel Time, Traffic Volume, Total Travel Time

Table 3 and Table 4 present a summary of the data analysis of the parameters examined: travel time (TT), traffic volume (Vol), and total travel time (TTT), before the truck prohibition and after truck prohibition, respectively. The measurement unit of the parameter total travel time is: [vehicle · hours]. Its total values (measured by vehicle · hours) in Table 3 and Table 4 indicate the total travel time in the system (segments 1-8) during the analysis period. The average travel time appears in minutes-seconds format. The total travel time appears in hours-minutes-seconds format (partial seconds are taken into account in the before-after analysis).

Figure 3 present graphically the "before and after" truck prohibition results of the traffic speed parameter (S). The results presented in Tables 3 and 4 and in Figures 3 encompass the before-after two-sample t-test results (i.e., analyzed results) of the average travel time, total travel time, and average speed parameters.

From Tables 3 and 4, we can observe that the weighted average travel time of all vehicles is almost identical to the average travel time of the light vehicles, since their volume governs the traffic stream.

Heavy and Medium Vehicle Traffic Volume Evaluation:

It appears that the implementation of truck prohibition significantly affected the medium vehicle type (single unit trucks) but affected only slightly the heavy vehicle type (percentage reduction

Table 1: "Before-After" Travel Times for Arazim-Harel Segment: 17:00-17:30

Arazim-Harel 17:00-17:30	**Travel Time (minutes), before truck prohibition**			**Travel Time (minutes), after truck prohibition**		
Vehicle type	**Light**	**Medium**	**Heavy**	**Light**	**Medium**	**Heavy**
Number of observations (n)	10	8	17	12	9	12
Mean (m)	6.13	6.54	6.97	3.99	4.18	4.52
Standard deviation (s)	0.597	0.381	0.399	0.6275	0.353	0.794
Coefficient of variance (s/m)	9.74%	5.83%	5.72%	15.72%	8.45%	17.55%
$W_i = s^2/n$	0.0356	0.0182	0.0094	0.03281	0.01384	0.05254
Estimated degree of freedom (d.f.)				19.61	14.41	14.95
t (d.f., 0.05/2)				2.093	2.14479	2.14479
t (actual)				8.18	13.22	9.85
p-value				1.203E-07	2.667E-09	1.1322E-07
Significance				*significant*	*significant*	*significant*
Sample size verification						
Confidence level	95%	95%	95%	95%	95%	95%
t (df, 0.05/2)	2.26	2.36	2.11	2.20	2.306	2.201
Critical precision level, D(%)	±7.0%	±5.0%	±3.0%	±10.0%	±6.5%	±11.2%
Computed sample size	9.90	7.59	16.36	11.98	8.98	11.90

difference of 33.4% vs. 1.1%, correspondingly, Table 5). A possible reason is that most heavy vehicles during the afternoon peak hours (16:00-18:00) were non prohibited vehicles, i.e., mostly public transport buses which are more frequent during the afternoon rush hours, and partially permitted vital trucks weighting more than 12 tons.

Table 5 summarizes the traffic volume of medium plus heavy vehicles, which basically consist of all slower vehicles in the traffic stream including buses, which are faster than trucks. Table 5 indicates that the truck prohibition reduced 15.4% of the weighted average traffic volume of

Table 2: Summary of Results of the "Before-After" Analysis of the Arazim-Harel Segment: 16:00-18:00

	d.f.	t (actual)	p-value (2 tailed)	Average Travel Time (min.): Before (observed)	Average Travel Time (min.): After (observed)	Significance	Average Travel Time (min.): Before (analyzed)	Average Travel Time (min.): After (analyzed)
Light vehicle								
16:00-16:30	18.96921	7.4353	6.84E-07	00:07:08	00:05:31	significant	00:07:08	00:05:31
16:30-17:00	15.21708	9.6167	8.336E-08	00:07:02	00:05:12	significant	00:07:02	00:05:12
17:00-17:30	19.60568	8.1796	1.203E-07	00:06:08	00:03:59	significant	00:06:08	00:03:59
17:30-18:00	8.294433	10.832	4.66E-06	00:05:40	00:02:58	significant	00:05:40	00:02:58
Medium vehicle								
16:00-16:30	17.1888	5.1327	8.309E-05	00:07:21	00:06:09	significant	00:07:21	00:06:09
16:30-17:00	9.980035	4.0333	0.00296	00:07:24	00:05:45	significant	00:07:24	00:05:45
17:00-17:30	14.40968	13.223	2.666E-09	00:06:33	00:04:11	significant	00:06:33	00:04:11
17:30-18:00	22.90058	6.42	1.8493E-06	00:05:43	00:03:33	significant	00:05:43	00:03:33
Heavy vehicle								
16:00-16:30	23.04125	4.7235	9.272E-05	00:08:31	00:06:11	significant	00:08:31	00:06:11
16:30-17:00	16.78354	11.046	6.763E-09	00:07:54	00:05:35	significant	00:07:54	00:05:35
17:00-17:30	14.94766	9.8457	1.132E-07	00:06:58	00:04:26	significant	00:06:58	00:04:26
17:30-18:00	16.85941	5.1498	9.686E-05	00:05:44	00:03:31	significant	00:05:44	00:03:31

medium plus heavy vehicles. This percentage is significant taking into account that buses, which are not prohibited (and are generally estimated in Highway 1 as approximately half of total heavy plus medium vehicles), are included in this calculation. The percentage of these two vehicle types in the traffic stream (from the total volume of light + medium + heavy vehicle) was reduced from 7.0% to 6.0% after truck prohibition.

The weighted average of traffic volumes of all eight segments was based on segment length in order to obtain these equivalent percentages.

Table 3: Data Analysis of Traffic Volume, Travel Time, and Total Travel Time Before the Prohibition (16:00-18:00)

Hgwy 1 West: (before)	**Average travel time (min.) 16:00-18:00**			**Total 16:00-18:00**
Before Restriction (full data)	Light vehicles	Medium vehicles	Heavy vehicles	
Sakharov Gardens - Arazim (1)	0:02:11	0:02:08	0:02:05	0:02:11
Arazim - Harel (2)	0:06:29	0:06:49	0:07:14	0:06:31
Harel - Hemed (3)	0:01:27	0:01:39	0:01:46	0:01:28
Hemed - Shoresh (4)	0:03:57	0:04:15	0:04:09	0:03:58
Shoresh - Shaar Hagai (5)	0:05:14	0:05:53	0:06:14	0:05:17
Shaar Hagai - Latrun (6)	0:02:34	0:02:51	0:02:54	0:02:36
Latrun - Anava (7)	0:04:39	0:05:22	0:05:19	0:04:42
Anava - Daniel (8)	0:02:30	0:02:52	0:02:52	0:02:32
	Number of vehicles 16:00-18:00			**Total 16:00-18:00**
Sakharov Gardens - Arazim (1)	3863	116	210	4189
Arazim - Harel (2)	6298	210	269	6777
Harel - Hemed (3)	5100	192	146	5438
Hemed - Shoresh (4)	5289	211	243	5743
Shoresh - Shaar Hagai (5)	5316	154	211	5681
Shaar Hagai - Latrun (6)	4323	145	183	4651
Latrun - Anava (7)	4208	126	175	4509
Anava - Daniel (8)	3799	141	156	4096
Weighted Average	**4683**	**156**	**195**	**5034**
	Total travel time (vehicle·hours) 16:00-18:00			**Total 16:00-18:00**
Sakharov Gardens - Arazim (1)	140:45:49	4:08:20	7:17:12	152:11:22
Arazim - Harel (2)	680:36:44	23:52:03	32:26:02	736:54:49
Harel - Hemed (3)	122:46:28	5:15:35	4:17:14	132:19:17
Hemed - Shoresh (4)	348:30:21	14:56:25	16:50:14	380:17:01
Shoresh - Shaar Hagai (5)	463:25:37	15:06:29	21:53:33	500:25:38
Shaar Hagai - Latrun (6)	185:27:45	6:53:11	8:51:54	201:12:50
Latrun - Anava (7)	326:32:03	11:15:41	15:30:10	353:17:54
Anava - Daniel (8)	158:47:37	6:44:59	7:26:21	172:58:57
Total (vehicle·hours)	**2426:52:24**	**88:12:43**	**114:32:41**	**2629:37:49**

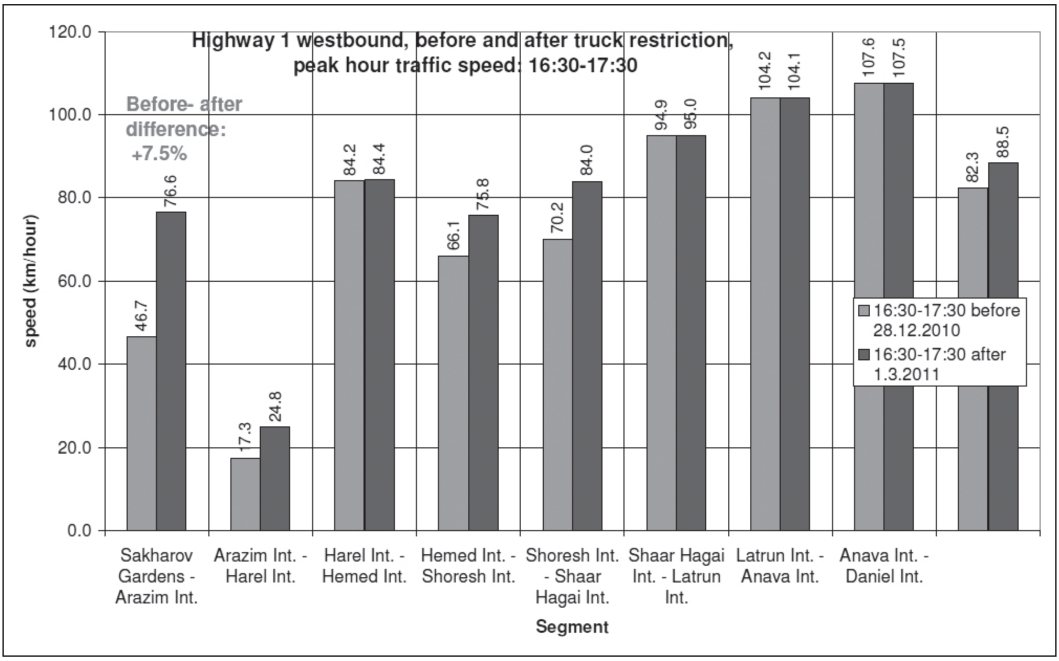
Table 4: Data Analysis of Traffic Volume, Travel Time, and Total Travel Time After the Prohibition (16:00-18:00)

Hghwy 1 West: (after)	**Average travel time (min.) 16:00-18:00**			**Total 16:00-18:00**
After Restriction (full data)	Light vehicles	Medium vehicles	Heavy vehicles	
Sakharov Gardens - Arazim (1)	0:01:29	0:01:40	0:01:41	0:01:30
Arazim - Harel (2)	0:04:28	0:05:04	0:05:03	0:04:28
Harel - Hemed (3)	0:01:27	0:01:39	0:01:47	0:01:27
Hemed - Shoresh (4)	0:03:32	0:03:48	0:03:49	0:03:33
Shoresh - Shaar Hagai (5)	0:05:12	0:05:14	0:05:52	0:05:13
Shaar Hagai - Latrun (6)	0:02:38	0:02:51	0:02:51	0:02:39
Latrun - Anava (7)	0:04:38	0:05:14	0:05:14	0:04:41
Anava - Daniel (8)	0:02:31	0:02:52	0:02:52	0:02:32
	Number of vehicles 16:00-18:00			**Total 16:00-18:00**
Sakharov Gardens - Arazim (1)	4127	67	197	4391
Arazim - Harel (2)	6596	141	235	6972
Harel - Hemed (3)	5151	118	126	5395
Hemed - Shoresh (4)	5283	123	235	5641
Shoresh - Shaar Hagai (5)	5374	116	201	5691
Shaar Hagai - Latrun (6)	4557	95	185	4837
Latrun - Anava (7)	4194	107	192	4493
Anava - Daniel (8)	3281	62	160	3503
Weighted Average (vehicles)	**4683**	**104**	**193**	**4980**
	Total travel time (vehicle·hours) 16:00-18:00			**Total 16:00-18:00**
Sakharov Gardens - Arazim (1)	101:56:24	3:06:12	5:30:14	110:32:49
Arazim - Harel (2)	490:09:50	17:59:42	19:44:55	527:54:28
Harel - Hemed (3)	123:47:20	4:40:58	3:44:47	132:13:06
Hemed - Shoresh (4)	310:41:26	11:00:40	14:54:58	336:37:03
Shoresh - Shaar Hagai (5)	465:16:41	13:52:50	19:37:55	498:47:26
Shaar Hagai - Latrun (6)	199:58:01	6:44:44	8:46:57	215:29:42
Latrun - Anava (7)	324:25:56	13:00:49	16:44:13	354:10:57
Anava - Daniel (8)	137:13:50	4:24:17	7:38:43	149:16:49
Total (vehicle·hours)	**2153:29:28**	**74:50:11**	**96:42:41**	**2325:02:19**

Table 5: Impact Summary of Truck Restriction on Combined Traffic Volume of Medium Plus Heavy Vehicles (16:00-18:00)

Segment	Before		After				
	Medium + heavy vehicle volume	Medium vehicle volume	Medium + heavy vehicle volume	Medium vehicle volume	Percentage difference (before-after): medium + heavy vehicle	Percentage difference (before-after): medium vehicle	Percentage difference (before-after): heavy vehicle
Sakharov Gardens - Arazim (1)	326	116	264	67	-19.02%	-42.24%	- 6.19%
Arazim - Harel (2)	479	210	376	141	-21.50%	-32.86%	- 12.64%
Harel - Hemed (3)	338	192	244	118	-27.81%	-38.54%	- 13.70%
Hemed - Shoresh (4)	454	211	358	123	-21.15%	-41.71%	- 3.29%
Shoresh - Shaar Hagai (5)	365	154	317	116	-13.15%	-24.68%	- 4.74%
Shaar Hagai - Latrun (6)	328	145	280	95	-14.63%	-34.48%	1.09%
Latrun - Anava (7)	301	126	299	107	-0.66%	-15.08%	9.71%
Anava - Daniel (8)	297	141	222	62	-25.25%	-56.03%	2.56%
Weighted average volume (based on segment length)	**351**	**156**	**297**	**104**	**-15.4%**	**-33.4%**	**-1.06%**

Figure 3: Before and After Traffic Speeds (S)



EXAMINATION OF THE PILOT STUDY PARAMETERS

The following parameters were examined before and after the truck prohibition: average travel time (ATT), total travel time (TTT) for the whole prohibition period (16:00-18:00), and average travel speed (S) for the peak hour (16:30-17:30) of the prohibition period. The percentage difference between before and after application of the truck prohibition was computed for each parameter. The computations were performed for the individual segment and for the total highway section. Equations (9) and (10) show the computations only for the ATT parameter. The computations for the two other parameters (TTT, S) examined to test the success of the pilot study were conducted in a similar format.

Percentage Difference for the Individual Segment:

$$(10)\quad \%ATT_k = \frac{(ATT_k(A)) - (ATT_k(B))}{(ATT_k(B))}$$

ATT_k (A) – average travel time for segment k after the truck prohibition
ATT_k (B) – average travel time for segment k before the truck prohibition
$\%ATT_k$– Travel time percentage difference before and after the truck prohibition for segment k.

Percentage Difference for the Whole Section:

$$(11)\quad \%ATT = \frac{(ATT(A)) - (ATT(B))}{(ATT(B))}$$

ATT (A) – average travel time for the whole highway section after the truck prohibition.
ATT (B) – average travel time for the whole highway section before the truck prohibition.

%ATT– Travel time percentage difference before and after the truck prohibition for the whole highway section.

Tables 6.1-6.3 present a summary of the analyzed results and the percentage difference of the three traffic parameters analyzed: ATT, TTT, and respective average speeds after implementation of the t-test results. The format of ATT and TTT in Tables 6.1, 6.2 is the same as in Table 3 and Table 4, i.e., minutes-seconds and hours-minutes-seconds, correspondingly. A decimal format of minutes and hours was supplemented in parentheses.

The analyzed results are based on equalizing of the non-significant sample outcomes for the purpose of examining the pilot study.

The results show that the pilot study was successful in regard to the three analyzed parameters: the ATT per vehicle decreased by 11.0%; the TTT decreased by 11.6%; and the average speed increased by 7.5%. The prohibition of trucks during the afternoon peak hours assisted in relieving congestion even though the total traffic volume slightly increased (Figure 2).

Table 6.1: Average Travel Time Results (Analyzed), Before and After Truck Prohibition

Road segment (16:00-18:00)	Distance (km)	Avg. TT per vehicle (min.): Before [analyzed]	Avg. TT per vehicle (min.): After [analyzed]	% difference Avg. TT per vehicle: [analyzed]
Sakharov Gardens - Arazim (1)	1.914	0:02:11 (2.180)	0:01:30 (1.494)	-31.5%
Arazim - Harel (2)	1.912	0:06:31 (6.524)	0:04:28 (4.469)	-31.5%
Harel - Hemed (3)	2.064	0:01:28 (1.460)	0:01:27 (1.454)	-0.4%
Hemed - Shoresh (4)	4.676	0:03:58 (3.973)	0:03:33 (3.546)	-10.7%
Shoresh - Shaar Hagai (5)	6.588	0:05:17 (5.285)	0:05:13 (5.219)	-1.3%
Shaar Hagai - Latrun (6)	4.076	0:02:36 (2.596)	0:02:39 (2.645)	1.9%
Latrun - Anava (7)	8.098	0:04:42 (4.701)	0:04:41 (4.681)	-0.4%
Anava - Daniel (8)	4.600	0:02:32 (2.534)	0:02:32 (2.532)	-0.1%
Total (minutes)	33.928	**0:29:15 (29.253)**	**0:26:02 (26.041)**	**-11.0%**

Table 6.2: Total Travel Time (TTT) Results (Analyzed), Before and After Truck Prohibition

Road segment (16:00-18:00)	Distance (km)	TTT (vehicle·hours): Before [analyzed]	TTT (vehicle·hours): After [analyzed]	% difference Avg. TTT: [analyzed]
Sakharov Gardens - Arazim (1)	1.914	152:11:22 (152.189)	110:32:49 (110.547)	-27.4%
Arazim - Harel (2)	1.912	736:54:49 (736.914)	527:54:28 (527.908)	-28.4%
Harel - Hemed (3)	2.064	132:19:17 (132.321)	132:13:06 (132.218)	-0.1%
Hemed - Shoresh (4)	4.676	380:17:01 (380.283)	336:37:03 (336.618)	-11.5%
Shoresh - Shaar Hagai (5)	6.588	500:25:38 (500.427)	498:47:26 (498.790)	-0.3%
Shaar Hagai - Latrun (6)	4.076	201:12:50 (201.214)	215:29:42 (215.495)	7.1%
Latrun - Anava (7)	8.098	353:17:54 (353.298)	354:10:57 (354.182)	0.3%
Anava - Daniel (8)	4.600	172:58:57 (172.983)	149:16:49 (149.280)	-13.7%
Total (vehicle·hours)	33.928	**2629:37:49 (2629.630)**	**2325:02:19 (2325.039)**	**-11.6%**

Table 6.3: Peak-Hour Travel Speed (S) Results (Analyzed), Before and After Truck Prohibition

Road segment (16:30-17:30)	Distance (km)	Avg. S (km/hr): Before [analyzed]	Avg. S (km/hr): After [analyzed]	% difference Avg. Speed: [analyzed]
Sakharov Gardens - Arazim (1)	1.914	46.7	76.6	64.1%
Arazim - Harel (2)	1.912	17.3	24.8	43.6%
Harel - Hemed (3)	2.064	84.2	84.4	0.2%
Hemed - Shoresh (4)	4.676	66.1	75.8	14.7%
Shoresh - Shaar Hagai (5)	6.588	70.2	84.0	19.7%
Shaar Hagai - Latrun (6)	4.076	94.9	95.0	0.1%
Latrun - Anava (7)	8.098	104.2	104.1	0.0%
Anava - Daniel (8)	4.600	107.6	107.5	0.0%
Entire section	33.928	**82.3**	**88.5**	**7.5%**

The improvement in average travel time (ATT) and speed (S) resulting from the truck prohibition was significant along segments 1, 2, and 4. The TTT parameter showed a significant improvement in segments 1, 2, 4, and 8. The speed (S) parameter showed a significant improvement in segment 5, too (during the peak hour 16:30-17:30). This improvement is balanced during the entire truck restriction period (16:00-18:00) due to an exceptional advantage in the ATT during the first half-hour period (16:00-16:30) before the truck prohibition. These improvements imply that the presence of trucks in the traffic stream disrupt the regular highway traffic. Essentially, drivers need to make difficult maneuvers of passing and lane changing, which could entail rear-end or side-end collisions.

The pilot study results showing improvements in the three parameters offer a good reason for implementing the truck prohibition only along segments 1-4. However, since there is no feasible alternative route to these segments for trucks, the Ministry of Transportation (MOT) implemented the truck prohibition along the entire section (segments 1-8) as originally planned.

QUALITATIVE EVALUATION AND DISCUSSION OF ROAD-SEGMENT GRADE EFFECT AND HCM PROCEDURE

The grade effect was evaluated to examine whether the grade level of each road segment was correlated with an improvement in traffic flow parameters. Table 7 presents the longitudinal grade level of the eight road segments. A summary is also provided of the percentage difference of the three traffic flow parameters, based on the analyzed results of Tables 6.1-6.3. The percentages in Table 7 are given as improvement percentages in order to unify the results to one average improvement outcome for each road segment.

Table 7 shows that improved average percentage results are correlated with longitudinal grade level. The level terrain corresponds to 0-2%; the moderate grade level corresponds to 2.1-4%; and the steep terrain corresponds to 4.1-6%.

Road segments 1, 2, and 4, which have the most significant improvements, have full or partial steep grades (either a steep descent or a steep rise). Segments 1 and 2, each of which presents a full, steep longitudinal grade, have the best percentage improvements (41% and 35%, respectively). Road segment 4, which has a partially steep and partially level terrain, resulted in a lower percentage improvement (12.3%) after the truck restriction. Segment 3 is the only segment for which there was no percentage improvement even though it has a steep grade along 55% of its alignment. This can be explained by the fact that the segment has much less horizontal curvature than do segments 1, 2, and 4, and is the only segment that has an additional lane per direction. The travel speed along Segment 3 was comparatively high even before the truck prohibition (approximately 85 km/hour) apparently because of its relatively straight descent and supplementary lane.

Road segments 5 and 8, which have no steep grade (a partial alignment of level terrain and a partial alignment of a moderate longitudinal grade), have a lower percentage improvement in the traffic flow parameters from the truck restriction. Road segments 6 and 7, whose terrain is partially level and partially moderate (similar to segments 5 and 8), have no percentage improvement in the traffic parameters examined. It appears that since the rise in the alignment of segments 5 and 8 is more than that of segments 6 and 7, the impact of the truck restriction on the former two segments is larger. The moderate rise causes more reductions in truck speed than does a moderate descent (or a level terrain) and, therefore, a better improvement in the traffic flow parameters with the truck prohibition.

Generally, the effect of a steep grade is correlated with the exclusion of heavy trucks from the traffic stream in terms of saving travel time and increasing the speed of the traffic stream. This outcome is relatively consistent with Cate and Urbanik's (2004) study, which concluded that a left-lane restriction—not a directional truck restriction as examined in this study—improved travel time with an increased grade but at lower percentages than found in the current study.

Highway Capacity Manual (HCM) Relevance Discussion

The Highway Capacity Manual (2000, 2010) provides a procedure for estimating the impact of different trucks' percentage with consideration of highway grades. Theoretically, the implementation of time of day restriction strategy, utilized in the current study (by prohibiting trucks from all lanes per direction), could be based on the HCM procedure after measuring the traffic volumes only (before and after truck restriction) by vehicle type.

HCM Procedure Overview for Implementation in the Current Study. The HCM procedure (for basic freeway segments or multi-lane highway segments) uses the heavy vehicle adjustment factor (f_{HV}) to calculate the equivalent passenger car flow rate (Vp) and finally evaluates the section Level of Service (LOS).

The equivalent passenger car flow rate (Vp) can be determined by the equation:

$$(12)\quad V_P = \frac{V}{\left(PHF \cdot f_{HV}\right)}$$

V: hourly volume (vehicle/ hour)
PHF: peak hour factor.

On the basis of the flow rate, Vp, and the speed-flow curves proposed by HCM (2000, 2010) and estimation of the actual Free Flow Speed (FFS), the average speed and the resulted average travel time of a specific segment can be determined.

HCM Procedure Limitations for the Purpose of the Current Study. The HCM procedure has some limitations for obtaining the average speed and the resulted average travel time, which are essential parameters to evaluate the success of implementing the truck prohibition in the current study.

The advantage of the procedure proposed in the current study is the determination of average travel time and average speed parameters of a specific segment by direct measurements without the need of several steps to obtain these parameters.

The HCM procedure does not provide the travel time and speed parameters directly. The composite grade along a specific segment and the multi-stage HCM methodology (e.g., Exhibit 23.1 in HCM 2000 for basic freeway segments) including the FFS approximation requirement, make the use of HCM procedure prolonged and probably prone to inaccuracies, especially for the current pilot segments' analysis. Also, the HCM flow-speed curves of basic freeway or multi-lane segments are

Table 7: Qualitative Level of Longitudinal Grade Effect and Percentage Improvement in ATT, TTT, and Speed

Road segment	Distance (km)	Longitudinal grade level	% improvement Avg. TT per vehicle: [analyzed] 16:00-18:00	% improvement Avg. TTT per vehicle: [analyzed] 16:00-18:00	% improvement Avg. Speed: [analyzed] 16:30-17:30	Avg. % improvement
Sakharov Gardens - Arazim (1)	1.914	**SD**	31.5%	27.4%	64.1%	41.0%
Arazim - Harel (2)	1.912	**SR**	31.5%	28.4%	43.6%	34.5%
Harel - Hemed (3)	2.064	55% **SD**, 45% MD	0.4%	0.1%	0.2%	0.23%
Hemed - Shoresh (4)	4.676	50% **SR**, 50% LT	10.7%	11.5%	14.7%	12.3%
Shoresh - Shaar Hagai (5)	6.588	35% MD, 30% MR, 35% LT	1.3%	0.3%	19.7%	7.1%
Shaar Hagai - Latrun (6)	4.076	40% LT, 60% MD	-1.9%	-7.1%	0.1%	-2.97%
Latrun - Anava (7)	8.098	45% LT 45% MD 10% MR	0.4%	-0.3%	0.0%	0.03%
Anava - Daniel (8)	4.600	35% LT, 45% MD, 25% MR	0.1%	13.7%	0.0%	4.6%

SD=Steep Descent, SR=Steep Rise, LT=Level Terrain, MD=Moderate Descent, MR=Moderate Rise limited to average speeds that are not lower than 50 km/hr, whereas speeds lower than 50 km/hour, which are considered LOS F in the HCM procedure, were observed in the current study.

Nonetheless, the HCM procedure which requires traffic volume data and trucks' composition only, is essential and fundamental for obtaining the traffic flow LOS. If we consider the average travel speed and calculate the flow rate based on traffic volume and travel time measurements per segment, we can derive the flow density (in passenger cars per hour per lane) and eventually evaluate the LOS of each segment (hourly based) without referring to the speed-flow curves of HCM.

POLICY CONSIDERATIONS

Israel MOT policy regarding truck restriction also includes directing heavy truck traffic (which is restricted in Highway 1) to an alternate route. This route is multi-lane highway 443, which can transfer truck traffic from the Jerusalem exit to the Modi'in area (Ben Shemen Interchange) and merge to Highway 1-westbound (Figure 4). Different policies such as a High Occupancy Toll (HOT) lane or a lower speed lane have been found not practical in terms of traffic load Right of Way (ROW) constraints. In most Highway 1 segments, there are two lanes per direction and the right shoulder is not continuously wide enough to be used as a peak period traveling lane for heavy trucks, without depreciating traffic flow if one of the two regular lanes (e.g., a lower speed limit lane) is prohibited for regular traffic.

The threshold of a 12-ton truck weight is a compromised strategy of Israel MOT in order to minimize the economic disadvantage to trucking companies and industry manufacturers. One rear-axle trucks, which weigh less than 12 tons, are characterized by better speed–distance curves' performance for tangent grades and also a better performance during their acceleration while making a merging maneuver from an interchange entrance ramp terminal. The larger dimensions of heavy trucks cause a significant disturbance to the traffic stream, increase the conflicts between vehicles, and therefore have a higher potential for traffic accidents. Nonetheless, this strategy reduced significantly the volume of medium vehicles in the traffic stream (compared with heavy vehicle type), including one rear-axle single unit (SU) trucks that could weigh more than 12 tons (Table 5). A typical commercial vehicle, which is implemented for designing climbing lanes in Israel and in other countries (Canada, TAC ATC 1999; PIARC 2003, Barton 2009, Ireland TD 2007 etc.), has a mass/power ratio of 8 HP/ton (170 kg/kwatt, 5.9 Kwatt/ton). This property usually matches the 12-ton trucks. According to Israel MOT traffic regulations and other sources (Hardwood et al. 2003), the threshold weight of two-axle vehicle SU trucks is 18 tons. This can clarify the outcome of significant decrease of medium vehicle types after truck prohibition.

Truck performance considerations and trucking companies' feedback directed Israel MOT to permit lighter trucks (weighing less than 12 tons) to continue using Highway 1. The option of determining different weight thresholds in different segments along the route examined may confuse truck drivers and is not feasible in terms of finding an alternate route and weight enforcement.

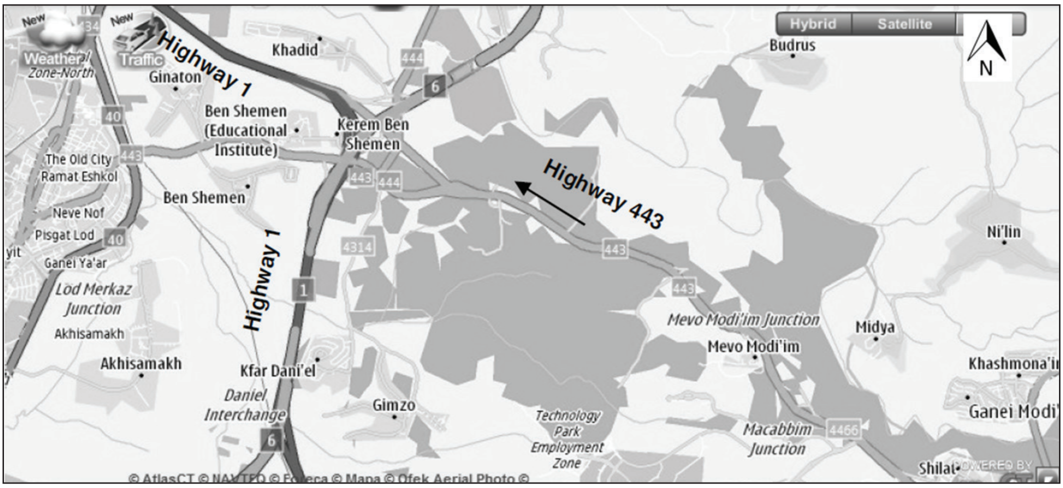
Road Pricing Potential

The amount of traffic in the analyzed section does not justify peak period road pricing strategy. Since the truck restriction strategy improved traffic flow, it was regarded as a reasonable policy solution, especially with integrating an alternate route.

In Israel, the access to the Tel Aviv metropolitan area by Highway 1 is more congested. Israel MOT considered overall road pricing as a possible solution but finally implemented a supplemental HOT lane toward Tel Aviv (westbound direction) from Ben Gurion International Airport. This solution was accompanied by constructing a large park & ride lot and allocating shuttle service to the passenger car drivers. This solution provides passenger car drivers the option to decide whether to follow the toll pricing policy, use the HOT lane and pay for the privilege, or park their car and use the shuttle bus service without paying, or continue using the regular congested lanes without saving travel time.

The topography of Ben Gurion Airport–Tel Aviv section is level terrain, so the problem of slow trucks is not prominent as in the Highway 1 studied section during the entrance to or the exit from the Jerusalem metropolitan area. It appears that the exclusion of trucks along the access to Tel Aviv would increase the regular traffic load of passenger cars anyway.

Figure 4: Merging from Highway 443 to Highway 1 (Ben-Shemen Interchange)



SUMMARY AND CONCLUSION

This study investigated the traffic operation efficiency gained by restricting heavy- truck traffic along 34 kilometers of Israel's Highway 1 in a westbound direction, exiting the city of Jerusalem during afternoon peak hours. The terrain of the section examined is partially hilly and includes several horizontal and vertical curves. The examination was performed during the rush hours although truck traffic volume does not necessarily tend to peak during the regular morning and afternoon commuter peaks. The possibility that trucks may cause a deterioration in both traffic flow quality and traffic capacity, the formation of long queues and merging, diverging, and weaving difficulties occurs during the peak hour period and not during the peak of truck traffic when the traffic stream is light.

The major objective of the study was to estimate the benefit of restricting truck traffic according to three traffic flow parameters: (1) average travel time (ATT), (2) total travel time (TTT), and (3) average traffic speed (S). The analyzed results, which considered the significant differences among samples during 30-minute periods based on two sample t-tests ("before-after" the truck restriction), show an 8%-12% improvement in all three traffic flow parameters by applying the truck prohibition to all lanes during the peak afternoon period of 16:00-18:00. Specifically, of the highway section examined, segments 1 and 2, each of whose full alignment consists of a steep longitudinal grade, experienced the most significant improvements in the parameters examined (41% and 35%, respectively). Road segment 4, which has a partial alignment of steep longitudinal grade and a partial alignment of level terrain, showed a lower percentage improvement (only 12%) than did road segments 1 and 2.

The combined results of the entire section examined (Sakharov Gardens-Daniel Interchange) reveal a consistent outcome of improved traffic flow insofar as all three parameters examined. This finding contrasts with some previous studies that evaluated the impact of lane-use restriction for trucks and that partially produced non-conclusive outcomes and even potential vehicle conflicts (e.g., merging and diverging conflicts along the right lane).

The methodology proposed by this study is preferable than the HCM Level of Service (LOS) multi-stage analysis procedure, which is subject to inaccuracies and is limited to higher portions of average travel speed.

We recommend to examine the results by additional data sets, and increased samples of travel time samples and by similar restrictions on additional rural freeways or multi-lane highway road segments because of the differences that could result from alternate geometrics, operational characteristics, and traffic pattern.

Furthermore, the methodology presented in this present study can be implemented on other roadways, rural or urban, with different geometric and traffic characteristics, especially highways carrying a significant amount of heavy vehicles that disrupt the traffic flow and risk the safety of passenger car drivers. Applying the present methodology on roadways having different operational and geometric characteristics from those in this study, such as urban freeways, might generate a different outcome. Prohibition of trucks in urban freeways during rush hours might bring additional daily passenger cars traffic to the traffic stream, which could negatively result in an insignificant improvement of traffic operation and even a slight deterioration of the traffic flow quality.

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APPENDIX A

Background: Vertical and Horizontal Curves in Highway Geometric Design

Proper design of roadway geometric design (design of road layout and road profile) is important to facilitate smooth flow of traffic and maintain traffic safety.

The basic principles of highway geometric design are generally exemplified for two highway alignment types: (1) roads with zero grade change direction (horizontal alignment), and (2) straight lines of the highway profile have different grades (vertical alignment). Although is it conceivable that two straight lines of the highway alignment that need to be joined, have different directions as well as different grades, the highway design have specific principles for horizontal alignment and vertical alignment.

Direction changes in road layout (horizontal alignment) are attained by providing curves between two straight lines in two different directions. These curves (generally circular curves) are termed horizontal curves.

Grade changes in roads are attained by providing curves between two straight lines at different grades along the highway profile (vertical alignment). These curves (generally parabolic curves) are termed vertical curves.

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