

Optimizing Truck Weigh Stations' Locations on the Highway Network of Saudi Arabia

Saad A. H. AlGadhi

*Associate Professor, Civil Engineering Department, College of Engineering,
King Saud University, P. O. Box 800, Riyadh 11421, Saudi Arabia*

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Abstract. This paper utilizes the deterministic flow-interception model with the objective of locating truck weigh stations to maximize the total flow of trucks that are intercepted during their travel on the intercity highway network of the Kingdom of Saudi Arabia (KSA). The Origin-Destination (O-D) matrix of daily truck trips between each pair of the KSA's 18 major cities and regional centers was assigned to the shortest paths between the O-D pairs. The flow interception model was then solved using two approaches: a mathematical programming (MP) approach and a (greedy) heuristic approach. The results show that the greedy heuristic gives a solution that is very close to the optimum in terms of the number of stations needed to intercept a given percentage of the truck flow. However, some of the station locations might not coincide with those given by the exact MP solution. Furthermore, the MP solution results show that 44 stations are needed for 100% truck flow interception, and that the existing 31 stations can intercept only 60.91% of the total truck flow. These 31 stations could intercept up to 98.73% of the total truck flow if relocated to the optimum locations.

Keywords: Truck weigh stations, Optimum locations, Saudi Arabia

Introduction

The Kingdom of Saudi Arabia (KSA) covers a sparse area of 2.25 million square kilometers, with a very low population density of 8 persons/km². The total population is 18 million with 78% living in urban areas [1]. These cities and towns are connected by a modern national highway network of about 45,000 km in length, in addition to more than 95,000 km of agricultural roads (paved and unpaved). The total investment in building this national highway network over a short span of two decades is about 132,000 million Saudi Riyals (US\$ 35 billion), with an additional 10% of the construction cost spent annually on highway maintenance [2]. It is essential that such a large investment in highway infrastructure be protected and maintained.

On the other hand, the rapid development of Saudi Arabia's highway system has accompanied a rapid increase in urbanization, development and industrialization. The trucking industry has developed rapidly in both volume and weight, with a fleet of more

than 81,000 trucks using the highway network for goods movement between and within urban areas [2].

The truck fleet owners, in an attempt to reduce their unit transportation cost (SR./ton-km), have often loaded their trucks to maximum capacity. These heavily loaded trucks have resulted in significant road and bridge damage [3]. Many of these fully loaded vehicles have exceeded the safety margins of their design components, and resulted in serious accidents due to loss of control. In 1983, a number of field studies indicated that 90 percent of all trucks weighed during those studies were in violation of the weight limits, carrying from 30 percent to as much as 300 percent more than the permissible loads [4].

The importance of load limits and highway design practices was recognized early in the history of highway development. This interrelation led directly to limitations on vehicle loads, and laws were enacted in many countries to establish maximum allowable motor vehicle sizes and weights [5]. As the highway system in the KSA matured, and there was a shift in emphasis from construction to maintenance and rehabilitation, the enforcement of motor vehicle size and weight laws became a highlighted issue. Strict enforcement of motor vehicle size and weight laws is a step toward reducing motor vehicle size and weight violations, heavy truck accidents, and, even more, highway maintenance and rehabilitation expenditures [3].

To protect the newly constructed highway network of the KSA, the Ministry of Communications (MOC) intervened in 1985, and established a trucks weight monitoring and control program. MOC started by building 5 weigh stations on some of the busy highways to control the weight of trucks. Currently, there are 31 weigh stations in operation (Fig. 1), 21 of them are equipped with permanent scales while the rest are equipped with portable scales [6].

MOC studies show that overloading violations before the weight limit enforcement were 32%, 54% and 43% for the 4-, 5- and 6-axle truck categories, respectively. The corresponding figures after enforcement are 4%, 12% and 33%, respectively [7]. Another independent study [4] evaluated the effect of the weight enforcement program on loaded trucks characteristics in the largest three of the five provinces of the KSA. The results showed much higher percentages of post-enforcement violations (e.g. for Eastern Province the corresponding percentages were 60%, 80% and 45%, respectively), and thus the study concluded that the current weight limit enforcement is insufficient. In fact, the actual problem might be much more serious if weigh stations (permanent or portable) locations were not strategically located on the highway network so as to intercept most, if not all, intercity trucks.

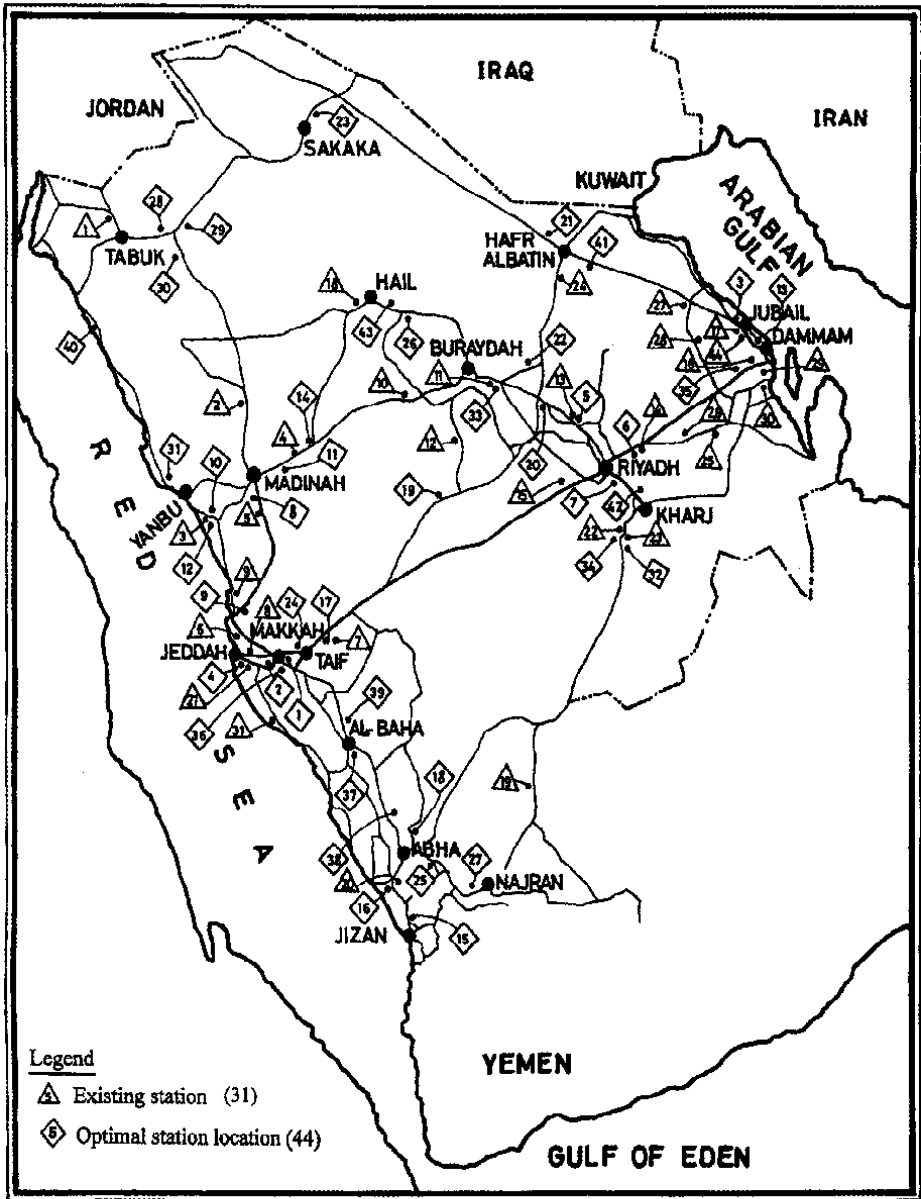


Fig. 1. Existing and optimum weight stations locations.

Thus, the objective of this paper is to evaluate and optimize the locations of truck weigh stations on the highway network of Saudi Arabia. Next section presents a review of relevant literature. Third section gives an overview of the theoretical background of the flow-interception facility location model adopted in this study. The application of this type of models to the research problem is presented in section four. Finally, section five presents the conclusions of this study.

Literature Review

Enforcement is a critical element of any plan for controlling vehicle weights. Effective enforcement must assure those who operate in violation of the established limits that they likely will be apprehended and will be given penalties and sanctions of sufficient magnitude to function as a deterrent [8]. Several studies were conducted to assess and evaluate truck weight regulatory policies [e.g., 9], and enforcement efforts [10, 11].

The purpose of a truck weighing program is to enforce legal load limits and thus prevent trucks from damaging highways and bridges. Essential to truck weight enforcement is the effective combination and deployment of the various types of scales (permanent, portable, and semi-portable). Through the use of data collected in truck traffic studies, permanent scales can be located where there are many overloaded trucks, and these scales can be supported by roving portable-scale crews [12].

The location of sites for permanent weigh stations, semi-portable stations, and supporting portable weigh units is basic to good truck weight enforcement. Many US states have conducted studies to determine the factors that should be considered in truck weigh stations' site selection. Two studies conducted in Georgia, USA identified the following items to be relevant: road systems and functional classifications, geographic location, traffic volume, season of the year, direction of route, service provided, product being transported, economic status of the transportation zone, and truck traffic patterns [12].

The US state agencies interviewed in the preparation of NCHRP SYN 82 [12] identified criteria to be used in selecting and evaluating a site after the route and general location are established by a truck traffic flow study. All the US state agencies recommend that the site be on a segment of highway that trucks cannot bypass.

Furthermore, NCHRP SYN 82 states that the best location for a weigh station (permanent or semi-portable) is adjacent to a natural obstacle, such as a large river or a swamp with few crossings. Geometric considerations are important in the site selection. Grades on the main highway should be gentle or slightly rising. The enforcing officer in the weighing house should have good visibility along both the main line and the ramps into the station. Distance between the weigh stations and interchange ramps should be sufficient to prevent any traffic conflict. Signing and visibility should allow the driver sufficient reaction time to maneuver the truck onto the weigh station ramps [12].

Permanent weigh stations are generally constructed around large metropolitan areas and along major truck movements. The NCHRP SYN 82 recommends establishing the truck routes and reviewing the truck patterns annually so as to design the permanent weigh sites for the loaded truck volumes. Natural barriers (e.g. rivers and swamps) should be used to the fullest extent possible.

California is one of the few US states that has prepared criteria for site selection. There, the primary consideration of selecting locations for permanent weigh stations is commercial vehicle traffic volume. The minimum average daily commercial vehicle count, exclusive of two-axle trucks, is set at 600 vehicles per day (both directions) for a permanent platform scale to be installed. Other criteria include considerations such as the following [12]:

1. Location of other facilities (existing or planned) on other highway routes should be accounted for.
2. Origin and destination counts should avoid double interception of a sufficient percentage of the commercial vehicle traffic.
3. Dual inspection facilities on each side of the highway should not be constructed if 80% or more of the trucks would be intercepted at one side of the highway.
4. Locations that can be bypassed easily must be avoided.
5. Sufficient land must be available.
6. And, other local conditions, e.g. utilities availability, climate, should be accounted for.

A Federal Highway Administration (FHWA) report [13] suggests numerous possible considerations for station site selection. These include:

1. average daily traffic volume;
2. percentage of trucks;
3. percentage of trucks of each type;
4. variations in the percentages of trucks carrying different types of commodities;
5. whether there is a seasonal variation in the number of trucks in the ADT, and whether within the season there is a variation in the type of commodities carried;
6. relative amount of interstate trips and intrastate trips;
7. land use characteristics, adjacent to the station site and at origin and destination of truck traffic;
8. ease-difficulty of trucks bypassing the station to avoid being weighed; and
9. nearby alternative routes.

Another study [14] suggested some guidelines for identifying general locations or corridors within which stations can be located:

1. Establish stations on routes with high truck volumes.
2. Locate stations on major intercity or interregional routes.

3. For stations on lower order roads, special care should be taken to avoid locations with atypical traffic conditions.
4. And, within the above criteria, stations should be located at or near vehicle classification sites or Automatic Traffic Recorder sites wherever possible.

A study [15] found that US state weight law enforcement programs were not adequate deterrents to overweight trucking. In response to this, the US Federal Highway Administration (FHWA) developed a three-point plan: (a) evaluate Weigh-in-Motion (WIM) equipment and promote its use by states, (b) evaluate scale avoidance by trucks that either bypass an open scale or stop and wait until scale is closed, and (c) develop and test a statistically valid prototype state weighing plan. WIM scales are also used quite effectively to screen trucks on busy highways so that only those trucks that appear to be operating above the legal or statutory weight limits are removed from traffic to be weighted on static or portable scales. Drivers of overweight trucks frequently are warned about weigh stations over citizen band (CB) radios and avoid scales by pulling over to the roadside until the scales are not in operation or by choosing an alternate route [15].

Truck weight data are routinely collected for estimating frequencies of each type of truck and year-to-year changes in axle and gross weights. Many studies and practice manuals are directed towards the selection of truck weigh sites based on a statistically-based sampling scheme designed to insure statistical representation [e.g. 8, 14, 16]. For example, the US Traffic Monitoring Guide states that the truck weight sample should consist of at least 90 measurements taken over a 3-year cycle with 1/3 of the sample concentrated on the Interstate highway system [8].

Finally, the MOC manual of locating weigh stations on highways states the following considerations in locating trucks weigh stations along the national highway network [17]:

1. clearance of the site from obstacles or private properties,
2. to be away from vertical and horizontal curves of the highway,
3. to be away from any drainage structures, e.g. culverts and bridges,
4. to be away from highway intersections,
5. ability of the site to serve many highways,
6. cannot be bypassed, and
7. to be at the right hand side of traffic flow direction.

It is obvious from the above review of both international and national criteria for selecting the locations of truck weigh station that they are generally local in nature and do not provide a macroscopic view of strategic and/or optimum locations.

On the other hand, the United Nations Economic and Social Committee for Western Asia (ESCWA) prepared a study on the general bases for planning and operation of truck weight monitoring stations in the Arab countries [18]. It states that

truck weigh stations should be located at a limited number of control points on the highway network so as to achieve the optimum utilization of available resources and to accomplish the system's objectives. These results motivated undertaking this study for the highway network of KSA.

Flow-interception Model Description

This section describes the mathematical program (MP) model adopted in this study, i.e. the flow-interception model. The presentation closely follows that of Berman, Hodgson and Krass [19]. In traditional network location theory, demand for service is assumed to originate from nodes of the transportation network, and the objective is usually to minimize either customers' average travel time (median problem) or the worst case travel time (center problem)[e.g., 20]. On the contrary, the flow-interception models are applicable when demand for service originates not from the nodes of the network but from flow (customers) travelling on various paths of the network. Therefore, the objective is to locate the facilities (e.g. trucks weigh stations) so as to maximize the total flow of customers (e.g. trucks) that are intercepted during their travel.

Flow-interception problems are classified into two major categories: the deterministic and the probabilistic models. In the former, it is assumed that there is complete knowledge of all the paths that carry non-zero flow in the network. The actual flows are also assumed to be known. In the probabilistic models, the information about paths and flows is not readily available. Rather it is assumed that only information on the fraction of customers originating their travel from any node and the fraction of customers that travel from any node to all adjacent nodes is given.

Data requirements make the deterministic formulation tractable only for the cases where the number of paths with non-zero flow is known. An important special case is when all flow occurs along the shortest paths connecting the origin-destination pairs. Actually, this is the case for truck flows along the intercity highway network, where congestion effects are lower than the fixed component of line-haul costs, in contrast to the situation in congested urban street networks. In the intercity case, assignment of the origin-destination (O-D) matrix will be an all-or-nothing [20]. That is, the flow between each O-D pair demand will be assigned to the shortest path connecting the origin and destination nodes. Therefore, this paper will adopt the deterministic flow interception model, which is described below.

The problem of locating m service facilities so as to maximize the total flow of potential customers who pass (are intercepted) by at least one of the facilities on their pre-planned trips was introduced independently in [21, 22]. Here we focus on the deterministic version of the problem where all paths between origin-destination pairs that carry non-zero traffic flow and the actual flow rates are known. Additional assumptions of the model discussed in [19] are:

1. Customers make no deviation, no matter how small, from their pre-planned tours to visit the facilities. It is not expected that a trucker will deviate from his route to be forced to stop at a weigh station.
2. Waiting time of customers at facility sites are negligible and do not affect the decision of the customer whether or not to visit the facility. In the mandatory truck weighing program regulated in the KSA this assumption holds.
3. And, customers are intercepted by at most one facility encountered along their route even if there are several facilities located at the route. In other words double counting of the intercepted flow is not allowed.

It seems that all these assumptions are reasonable and well fit to the research problem presented here, i.e. locating trucks weighing stations on the KSA highway network.

Problem formulation

Consider a network $G = (N, A)$, where N is the set of nodes with cardinality n and A is the set of arcs. Denote by P the set of non-zero flow paths in the network and by f_p the rate (per unit time) of flow along path $p \in P$. Denote the total flow by f , $f = \sum_{p \in P} f_p$. Suppose there are $m > 1$ facilities to be located in the network. The objective is to locate the facilities so as to maximize the total flow intercepted. Let X be a set of m points from G and $I(X, p)$ be an indicator variable that assumes the value 1 if at least one point in X is included in the path p and 0 otherwise. The problem is:

$$\max_{X \subseteq G, |X|=m} F(X) = \sum_{p \in P} f_p I(X, p) \quad (P_1)$$

The search for X can be limited to the set of nodes N and thus all interior points on arcs can be excluded from consideration. The reason is that any facility that is located on an interior point of an arc can be moved to either one of the two nodes connecting that arc without any loss of flow and possibly with a gain of additional flow. Therefore, $F(X)$ the set function in (P_1) is now defined for $X \subseteq N, |X| = m$.

The formulation of the problem above is graph theoretical. However, the problem can also be formulated as an integer programming problem. The formulation is very similar to that of Church and ReVelle's Maximal Covering Location Problem [23], and is given in [18] as follows:

Define two sets of decision variables:

$$X_j = \begin{cases} 1 & \text{if there is a facility located on node } j \text{ } j \in N \\ 0 & \text{otherwise} \end{cases}$$

and

$$Y_p = \begin{cases} 1 & \text{if at least one facility is located on path } p \text{ } p \in P \\ 0 & \text{otherwise} \end{cases}$$

The problem is

$$\max \sum_{p \in P} f_p Y_p \quad (P_2)$$

Subject to

$$\sum_{j=1}^n X_j = m \quad (1)$$

$$\sum_{j \in p} X_j \geq Y_p \quad p \in P \quad (2)$$

$$X_j = 0,1 \quad Y_p = 0,1 \quad (3)$$

Since Y_p is equal to 1 only if there is at least one facility located on path p , the flow rate f_p will be included exactly once (and double counting will be avoided) in the objective function when $Y_p = 1$. Constraint (1) guarantees that exactly m facilities are located. Constraints (2) and constraints (3) make sure that if no facility is located on path p , Y_p is equal to zero and if there is at least one facility on path p , since the objective function is a maximization of the sum of non negative terms, $Y_p = 1$. A branch and bound algorithm to give the exact solution of the problem is given in [22].

Greedy heuristic

Alternatively, a heuristic approach, known as the greedy heuristic, can also be used to solve the problem P_1 . The main idea of the greedy heuristic is to sequentially locate the facilities at nodes that intercept as much of the remaining unintercepted flow in the network as possible. At each step of the heuristic, the node that intercepts the maximum remaining flow is selected as the next new location. The greedy heuristic for P_1 takes the following steps:

Step 0: $X^0 = 0$, $N^0 = N$

Step 1: for $t = 1, \dots, m$: $j_t = \arg \max_{j \in N^{t-1} - X^{t-1}} F(X^{t-1} \cup \{j\})$;

$$X^t = X^{t-1} \cup \{j_t\}; \quad N^t = N^{t-1} - \{j_t\}$$

Step 2: Optimal solution is $X^* = X^m$ and optimal objective function is $F(X^*)$.

The greedy algorithm is initiated by having no facilities located on any of the network nodes, and thus no flow is intercepted. Then, for each facility t , $t = 1, \dots, m$, the t^{th} facility is located at the node that assures its interception of the maximum remaining (unintercepted) flow possible. After which the t^{th} node is added to the set of occupied nodes (X) and removed from the set of empty nodes (N). This procedure is repeated until all facilities, m , are located. Upon completion, the set of occupied nodes, X^* , represents the optimal solution set and the corresponding flow intercepted by these facilities is the maximum flow that could be intercepted by m facilities.

Extensive computational experience with the heuristic shows that, in most cases, it either provides the optimal solution, or a solution that is very close to the optimal one [19]. The problem P_1 was tested in the urban road network, with morning-peak traffic patterns, of Edmonton, Canada, which consisted of 23350 non-zero flow pairs, 703 nodes and 2198 links. The efficiency and robustness of the exact and the greedy procedures were compared, and the study found the greedy algorithm to be very efficient and robust [19].

The application of the deterministic flow-interception model to the national (intercity) highway network of the KSA to optimally locate truck weigh stations is given next for both the exact solution and the greedy heuristic, as well as the use of the model to evaluate the existing locations performance.

Model Application

Data setting

The data needed to utilize the deterministic flow-interception model include identification of all the paths that carry non-zero flow in the network and the actual flows on those paths. The approach employed to obtain these data uses the origin-destination matrix of truck trips between major cities and regional centers of the KSA. The study relied on the truck trips O-D matrix that was developed from a very extensive study of truck/cargo transportation on the KSA national highway system, as part of the Saudi Arabian National Transportation Plan (SANTRAPLAN)[24].

Due to space limitations, the truck trips O-D matrix is not shown here, however Table 1 shows the total trips produced and attracted to each of the major cities and regional centers, and their corresponding percentages of the total daily truck flow. The Table shows that there are about 60,000 daily loaded trucks flowing on the network in both directions between all origin destination pairs. More than half of the daily truck flow is generated by the cities of Jeddah, Riyadh, Dammam and Makkah, which generate 18.1%, 14.8, 11.2% and 10% of the total daily trips, respectively.

Table 1. Daily truck trip productions and attractions for major cities/centers

City/regional center	Trips produced and attracted	%	City/regional center	Trips produced and attracted	%
1. Hail	2048	3.4	10. Riyadh	8782	14.8
2. Sakaka	802	1.3	11. Kharj	2616	4.4
3. Tabuk	1236	2.1	12. Dammam	6632	11.2
4. Madinah	2454	4.1	13. Jubail	2284	3.8
5. Yanbu	1812	3.0	14. Hafr-Albatin	2080	3.5
6. Jeddah	10734	18.1	15. Al-Baha	620	1.0
7. Makkah	5930	10.0	16. Abha	1502	2.5
8. Taif	3672	6.2	17. Jizan	688	1.2
9. Buraydah	4722	7.9	18. Najran	826	1.4
Total			59440	100.0	

For each O-D pair, the shortest path was found by employing Dijkstra's shortest path algorithm [25] on the abstracted national highway network, resulting in 306 paths; the highway network was abstracted to consist of 130 nodes and 326 links. Average truck travel time on each link was estimated based on an average speed 100 km/hr for freeways, 50 km/hr for mountainous highways, and 80 km/hr for other main highways. The longest travel time is 1608 minutes (26.8 hours), which was on the path from Najran in the far south to Sakaka in the far north of the KSA, while the smallest times were about 50 minutes (from Riyadh to Kharj and from Jeddah to Makkah). After identifying these shortest paths, the O-D matrix was assigned using all-or-nothing assignment technique [20], resulting in an estimation of actual flows on each of the 306 shortest paths.

Exact solution

The flow-interception model is then formulated in accordance with mathematical program (MP) P₂. The MP was solved using a standard linear programming package, i.e. Lindo[®] software [26]. The number of weigh stations (m) was systematically varied to capture the marginal contribution of each weigh station on the overall flow intercepted. Table 2 summarizes the results of having a number of weigh stations ranging from one to the number required to intercept the total flow, which turned out to be 44 stations. However, at least 90% of the total flow can be captured by only 16 weigh stations, 95% by 22 station and 99% by 33 weigh stations. Figure 1 shows the optimum locations of the 44 weigh stations that guarantee complete truck flow interception.

Table 2. Number of optimally located stations and their total intercepted flow

Number of stations (m)	Total flow intercepted (Trucks/day)	% Intercepted	Number of stations (m)	Total flow intercepted (Trucks/day)	% Intercepted
01	7608	12.80	23	57124	96.10
02	14908	25.08	24	57390	96.55
03	21162	35.60	25	57634	96.96
04	26688	44.90	26	57862	97.35
05	31792	53.49	27	58040	97.64
06	36646	61.65	28	58218	97.94
07	39592	66.61	29	58388	98.23
08	42520	71.53	30	58540	98.49
09	45124	75.92	31	58688	98.73
10	47048	79.15	32	58814	98.95
11	48750	82.02	33	58914	99.12
12	50154	84.38	34	59012	99.28
13	51334	86.36	35	59094	99.42
14	52672	88.61	36	59158	99.53
15	53480	89.97	37	59220	99.63
16	54092	91.00	38	59270	99.71
17	54652	91.94	39	59316	99.79
18	55122	92.74	40	59350	99.85
19	55596	93.53	41	59378	99.90
20	56036	94.27	42	59406	99.94
21	56448	94.97	43	59430	99.98
22	56812	95.58	44	59440	100.00

Comparison with existing distribution

To compare the optimum weigh stations' locations shown above with the existing spatial distribution of weigh stations, the locations of the 31 weigh stations were input in the MP program P₂ by pre-specifying their current locations on the corresponding links. Nine of these stations were found to lie on links that do not belong to any of the 306 shortest paths, and were removed from further consideration. In fact, some of them were built on old highways that are now bypassed by the newly constructed and more direct highways (e.g. station no. 8, Fig.1). The MP was then run to calculate the total flow intercepted by the remaining 22 pre-located weigh stations. It was found that these weigh stations intercept only 60.91% of the total daily truck flow.

Furthermore, ignoring the three equipped stations that are located off shortest path links, the weigh stations that are equipped with permanent scales (21 stations of the existing 31 stations) intercept only 59.54% of the flow. This clearly explains the poor performance of the trucks' weight limit enforcement program in the KSA [4].

On the other hand, using the same total number of stations, the corresponding percent of trucks intercepted when optimally locating the stations (i.e. relocation) increases sharply to 98.73% (31 stations) and 94.97% (21 stations), respectively.

Table 3 shows the maximum flow that can be intercepted by each of the existing weigh stations, sorted in descending order of flow intercepted, when each is the only station on the network, at its current location. Note that the cumulative number of trucks intercepted by all stations, when adding the maximum flow intercepted by each singly located existing station, is almost 99.8% of the total flow, while the actual total flow intercepted is, as shown earlier, only 60.91% of total flow. This discrepancy is due to double counting of flow intercepted by more than one of the stations shown in Table 3.

Table 3. Flow intercepted by each existing weigh station

Station code (Fig. 1)	Total flow intercepted (Trucks/day)	% Intercepted	Station code (Fig. 1)	Total flow intercepted (Trucks/day)	% Intercepted
21	7510	12.66	09	1642	2.77
14	6236	10.51	15	1566	2.64
07	6004	10.12	20	938	1.58
17	5958	10.04	23	896	1.51
13	5104	08.60	22	756	1.27
04	4534	07.64	18	450	0.76
11	3810	06.42	31	396	0.67
10	3472	05.85	19	312	0.53
05	2928	04.94	02	302	0.51
16	2370	04.00	12	228	0.38
03	2262	03.81	Total	59320	100.00
24	1646	02.77			

Figure 1 shows both the locations of the existing 31 weigh stations, both equipped and non-equipped, and the optimum locations of the 44 stations that guarantee complete flow interception. The numbering scheme of the optimally located stations in Fig. 1 is in descending order of flow intercepted by each station. The truck flow intercepted by the optimal station number 1 is the highest, while that of station number 44 is the lowest.

Figure 1 shows that 13 of the existing weigh station locations (permanent scale-equipped and non-equipped) are, in fact, optimally located. These are the stations numbered 3, 4, 5, 7, 11, 13, 14, 16, 17, 21, 22, and 23. The total flow intercepted by these 13 stations, if they were the only stations on the network, was found, by re-solving the MP, to be 59.63%. The cumulative flow intercepted by these stations, when adding the maximum flow intercepted by each singly located existing stations, is 81.37% of total truck flow. Again, the discrepancy is due to double counting of flow intercepted by more than one of the stations.

Exact and greedy heuristic solutions comparison

The greedy heuristic was used to solve the same problem, and its results compared with the exact solution of MP problem P_2 shown above in Table 2. A Matlab[®] program [27] was written to solve problem P_2 using the greedy heuristic outlined in the previous section of the paper. The heuristic solution shows that 46 stations are needed to intercept the total flow, as compared with 44 stations for the exact solution. In addition, some differences appeared between the two solutions, as shown in Table 4.

Table 4 shows that the flow intercepted by each number of stations (m) in the exact and the heuristic solutions are almost the same. The maximum deviation is less than 1%. However, the set of station locations are drastically different; the difference in the number of optimal station locations between the two solutions approaches reaches as much as 38%.

Table 4. Comparison of exact and greedy heuristic (GH) solutions results

No. of Stations (m)	GH Total flow intercepted (Trucks/day)	% Deviation from exact solution	Number (%) of different stations	No. of stations (m)	GH total flow intercepted (Trucks/day)	% Deviation from exact solution	Number (%) of different stations
1	7608	0.00	0 (0)	24	57108	-0.49	6 (25)
2	14908	0.00	0 (0)	25	57410	-0.39	7 (28)
3	21162	0.00	0 (0)	26	57654	-0.36	6 (23)
4	26576	-0.42	1 (25)	27	57832	-0.36	7 (26)
5	31680	-0.35	1 (20)	28	58010	-0.36	6 (21)
6	36534	-0.31	1 (17)	29	58180	-0.36	9 (31)
7	39462	-0.33	2 (29)	30	58332	-0.36	9 (30)
8	42316	-0.48	2 (25)	31	58480	-0.35	7 (23)
9	45124	0.00	0 (0)	32	58606	-0.35	6 (19)
10	47036	-0.03	2 (20)	33	58704	-0.36	7 (21)
11	48480	-0.55	2 (18)	34	58804	-0.35	8 (24)
12	49884	-0.54	2 (17)	35	58898	-0.33	7 (20)
13	51262	-0.14	4 (31)	36	58980	-0.30	10 (28)
14	52196	-0.90	4 (29)	37	59060	-0.27	11 (30)
15	53004	-0.89	4 (27)	38	59124	-0.25	8 (21)
16	53798	-0.54	5 (31)	39	59186	-0.22	7 (18)
17	54410	-0.44	3 (18)	40	59248	-0.17	12 (30)
18	54982	-0.25	4 (22)	41	59298	-0.13	11 (27)
19	55422	-0.31	6 (32)	42	59344	-0.10	11 (26)
20	55810	-0.40	4 (20)	43	59406	-0.04	8 (19)
21	56174	-0.49	8 (38)	44	59406	-0.06	12 (27)
22	56488	-0.57	7 (32)	45	59430	-0.02	10 (22)
23	56800	-0.57	6 (26)	46	59440	0.00	10 (22)

Concluding Remarks

Highway agencies all over the world recognize that overweight trucks are a major cause of premature pavement and bridge deterioration. If an agency desires to effectively reduce the number of overweight vehicles, it might do so in a number of ways [28].

1. It might increase the likelihood that violators will be apprehended by increasing the level of enforcement.
2. The cost of violations to truckers once they have been apprehended might also be increased.
3. And, the cost of violations might be in the form of fines or actions (e.g. unloading excess weight) taken against the violator.

This paper addresses the first of these strategies, by finding the optimum weigh station locations needed to intercept most, if not all, loaded trucks operating on the highway network of the KSA.

The optimum weigh stations locations need not be occupied by permanent static scales. Enforcement of legal weight, driving statutes or truck inspection is usually carried out at these sites, thereby creating the opportunity for overloaded trucks or drivers aware of other violations to seek alternative routes or wait until the station is closed. Therefore, it might be more appropriate to utilize Weigh-in-Motion (WIM) scales. It offers a degree of concealment and anonymity that enhances data credibility since vehicles in violation, that normally may have deliberately bypassed a known weighing operation, are recorded at WIM sites.

In the exact solution of the MP, P_2 , it was assumed that drivers choose their routes between each O-D pair along the corresponding shortest path. All drivers would follow such route selection behavior only if the (invisible) WIM truck weigh scales are used, thus suppressing driver attempts to avoid the scales. However, if truck weigh stations locations are known a priori to truck drivers, some violating drivers might attempt to choose their routes based on avoiding the scales, instead of the shortest path between O-D pairs. Therefore, all-or-nothing assignment would be invalid for such drivers and another route assignment procedure that takes into consideration weigh station bypass behavior should be employed. Such an investigation is recommended for future research.

The approach utilized in this study should serve as the basis for the continuing effort to respond to the dynamic nature of truck flow routes and volumes on the KSA highway system. For example, the recent removal of a large number of fuel truck-trips per day from the truck traffic flowing from Dammam to Buraydah, due to the construction and operation of the new refined fuel pipeline joining these cities [29], might affect the optimum weigh station locations. Therefore, similar studies should be performed and updated periodically to ensure coping with the changing truck traffic flow trends and patterns.

Furthermore, this paper has adopted the deterministic approach to the flow-interception model. The author is undertaking a study of the same case study (i.e., the KSA highway network) utilizing the probabilistic model. The results of both the deterministic and the probabilistic approaches will be compared to test the robustness of the flow-interception model's application to this type of problems. Studies of other aspects of truck size and weigh monitoring program should be concurrently carried out to ensure the effectiveness of the truck weight monitoring program.

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تحديد المواقع المثلى لمحطات وزن الشاحنات على شبكة الطرق في المملكة العربية السعودية

سعد بن عبدالرحمن القاضي

أستاذ مشارك، قسم الهندسة المدنية، كلية الهندسة، جامعة الملك سعود،

ص.ب ٨٠٠، الرياض ١١٤٢١، المملكة العربية السعودية

(قدّم للنشر في ١٠/٢٢/٢٠٠٠م، وقُبل للنشر في ٢٦/٢/٢٠٠١م)

ملخص البحث. استخدمت الدراسة النموذج الرياضي غير الاحتمالي لاعتراض التدفقات لتحديد المواقع المثلى لمحطات وزن الشاحنات، التي تضمن تعظيم إجمالي عدد الشاحنات التي يمكن لتلك المحطات اعتراضها خلال تنقلها على شبكة الطرق التي تربط مدن المملكة العربية السعودية. وجرى تخصيص مصفوفة بدايات رحلات الشاحنات ونهاياتها بين المدن السعودية الرئيسة (١٨ مدينة) على أقصر المسارات بين كل مدينتين، ومن ثم حُلّ النموذج الرياضي بطريقتين أحدهما بالبرمجة الرياضية والأخرى باستخدام إحدى الخوارزميات المعروفة. وبينت النتائج أن الحل الخوارزمي كان قريباً جداً من الحل الأمثل من حيث عدد محطات الوزن اللازمة لاعتراض نسبة معينة من إجمالي حركة الشاحنات، ولكن قد لا تتوافق مواقع الشاحنات المحددة بالحل الخوارزمي مع المواقع المثلى. كما بين الحل الرياضي أنه يلزم توفير عدد ٤٤ محطة وزن، موزعة بطريقة مثلى، لكي يمكن اعتراض كامل لحركة الشاحنات على شبكة الطرق الوطنية، في حين لا تستطيع المحطات القائمة حالياً اعتراض سوى ٦٠.٩١٪ من إجمالي حركة الشاحنات. ويمكن زيادة تلك النسبة إلى ٩٨.٧٣٪ من خلال تغيير مواقع تلك المحطات القائمة إلى المواقع المثلى.