Traffic Flow Problem Simulation in Jordan
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Abstract:  - This paper presents the simulation of traffic flow on a congested street in the Jordanian capital Amman. The geometry, boundary conditions and assumptions were also compared against videos taken for actual traffic on the street. Although limited changes to the geometry is applicable in reality, some recommendations on speed limits and traffic signs were made to aid in reducing traffic jams.

Key-Words: - Traffic simulation, discrete fluid dynamics, Finite Element Modeling

1 Introduction
Old cities in the Middle East have faced rapid and sometimes random expansion in size with little attention to upgrading or expanding existing road networks to accommodate the ever-increasing vehicles density. Traffic jams outside of rush hour are the norm, prompting an effort to utilize finite element techniques to model road geometries and vehicular densities to arrive at a better understanding and isolation of the problem in order to devise proper solutions. The problem takes a higher weight in busy cities such as Amman, Jordan, where large-scale geometrical changes to roads are not possible due to limited spaces between buildings and projects.

The chosen location for applying the simulation was a vital street connecting Jamal Abdul Nasser square and the fourth circle in Amman. The street has one of the worst traffic jams in the capital because of the recently inaugurated link between eastern and western Amman through a tunnel that goes underneath the fourth circle. This has lead to increased traffic usage by vehicles choosing it as an alternative rout to original destinations, resulting in added strains on intersections. One location that is congested frequently throughout working days, and this is due to several reasons that are mostly geometrical. This location is shown in Figure 1 at point (1), where the traffic splits into two streams, a smaller one goes into a two-lane tunnel, while the other, larger one squeezes into an overpass at (2), where a small percentage of the cars turns right into a side road at (3).

The space available around the location makes any lateral extension of the road impossible, and thus it was an interesting problem to tackle at the attempt of understanding it and hence devise the proper approach to minimize if not eliminate congestion.

Many researchers have discussed the traffic flow problem and devised analytical and numerical methods to understand and simulate it. Many models have been constructed for traffic flow, such as cellular automaton (CA) models, the gas kinetic models, the hydrodynamic models and the car-following models.

One car-following models is the optimal velocity (OV) model proposed by Bando et al [1]. This model has successfully described the formation of traffic jams and reveals the transition mechanism between freely moving traffic and jammed traffic were described by linear stability analysis. The jamming transitions have the properties very similar to the conventional phase transition and critical phenomena. When car density is high, traffic jams occur and propagate as density waves. In the OV
model, acceleration of the car is described by a simple differential equation by using the optimal velocity function, which is depended on the headway (the distance between two successive cars), that is, the driver is supposed to look at the one and only car ahead. In more realistic situation, the driver considers more information of cars around him.

For developed countries flow, an interesting work studying capacity analysis for fixed-time signalized intersection for non-lane based traffic condition research by M. Hadiuzzaman and M. Mizanur Rahman [2] deals with development of saturation flow and delay models for pre-timed signalized intersections with reference to non-lane based traffic condition to account non-uniformity in the static and dynamic characteristics of the vehicles passenger car unit (PCU) values for each vehicle is found out using synchronous regression technique and a range of site-specific PCU values were obtained.

Finally, a MATLAB Model of Traffic Flow analysis based on “follow-the-leader” theories of traffic flow constructed by [3], constructed a simple model that allows the modeling of complicated behavior of flow considering a one-lane, one-way, circular path with a number of cars on it. Each driver slows down or speeds up on the basis of his or her own speed, the speed of the car directly ahead, and the distance to the car ahead. Human drivers have a finite reaction time and it takes them a certain amount of time (usually about a second) to observe what is going on around them and to press the gas pedal or the brake, as appropriate.

2 Problem Formulation

In this research, the vehicle flow will be simulated using the commercially available (ANSYS) software as fluid flow. Many assumptions will be introduced and applied to the specific geometry of the congested road fork shown in Figure 1 as will be discussed in the next section. Since collisions are not permitted, the flow can easily be assumed to be incompressible, and the density will be determined based on actual observation of the road, which was filmed and studied over extended periods of time, especially during rush hour (early morning 8:00-9:30 am and evenings 2:30-4:00pm).

The simulation will attempt to predict the conditions at which the flow becomes choked at the entrance of the road (region between points (1) and (2) in Figure 1). The choking happens when both the flow density and vehicular speeds are higher than the current geometry can handle, resulting in a sudden congestion that brings the vehicular velocities down to zero, resulting in a shockwave that will travel upstream (opposite to the traffic flow direction) and thus creating a traffic jam. This is expected to appear as a severe discontinuity in the simulated flow conditions (impossibly high velocities or pressures).

The above problem formulation will help predict the flow conditions at which congestion occurs and will also help devise some solutions to alleviate them by introducing some geometrical (road geometry) and/or flow (by a traffic controller) changes.

2.1 Simulation setup

The geometry used to simulate the road in ANSYS is shown in Figure 2. Effectively, the road has two lanes during traffic congestion, as the one of the lanes going into the tunnel (point (1) in Figure 1) and will be considered as a wall with zero velocity boundary condition, while the second lane will have traffic that will attempt merging with LANE1 before the tunnel starts, as seen in the figure. These attempts are not always successful as will be seen in later sections.

![Fig.2 Problem geometry](image)

The velocity boundary conditions applied on the entrance area were varied from 30 to 60 km/hr according to the speed limit of the road, and whether or not the flow is slowing down or speeding up.

The analytical equations governing the flow are similar to Navier-Stokes equations as follows [4]:

\[
\frac{\partial p}{\partial t} + V \cdot \frac{\partial p}{\partial x} = \rho C_v \frac{\partial^2 V}{\partial x^2} + \mu \frac{\partial V}{\partial x} - \frac{1}{\tau} (V_e - V)
\]

where,

- $t$: adaptation time
- $p$: flow density
- $\mu$: viscosity
- $C_v$: constant velocity of propagation

The density was determined by calculating the number of cars per kilometer from the recorded video and then setting the maximum number of cars within the simulation area as a the water density of 1000 kg/m³. This would serve the incompressibility assumption and at the same time can be used as the 100% density value that can be the basis for calculating the density when fewer cars are there per kilometer of the solution domain. This value was found to be 45 vehicles/area. The area is the
simulation domain area of 230x10.5 m$^2$. The minimum assumed vehicular density was calculated to be at 22 vehicles per the same area of the road. This was interpolated to be 444 kg/m$^3$, and used when simulating lower flow densities as will be seen later.

According to [2], in traffic dynamics the law of conservation of momentum (equation 2) is not valid, and instead, the term $\frac{(V_e-V)}{\tau}$ is called the relaxation term, where the velocity component in the flow direction, $V(x,t)$ is taken relative to a certain free stream velocity, $V_e$, within a certain time period, $\tau$. In ANSYS, the momentum equation was hence set to zero as it will not affect the analysis as per the above conclusion.

The element used for meshing was FLUID141, which is a two-dimensional, four-noded linear fluid element capable of calculating the velocity components in the x and y directions at each node. After meshing, a total of 187 elements formed the mesh, with a total of 280 nodes, as seen in Figure 3.

![Fig.1 Meshed solution domain](image1)

The simulation was run for conditions when the inlet velocity was set to 30 and 60 Km/hr, and as initial guesses, the velocity at the exit was given the values of 30 and 60 Km/hr for each initial inlet velocity value, resulting in four simulation runs for each density value.

### 3 Simulation Results

#### 3.1 Velocity Profiles

This section presents the results obtained by running the simulation for the following two-lane flow velocity conditions.

**3.1.1 Accelerating flow**

This is the case when the inlet velocity is set to 30 Km/hr, with 60 Km/hr initial guess exit velocity.

![Fig.4 Vin=30 Km/hr, Vout= 60 Km/hr](image2)

**3.1.2 Homogeneous flow**

In this case, the inlet velocity of 60 Km/hr equals the 60 Km/hr initial guess exit velocity.

![Fig.5 Vin=60 Km/hr, Vout= 60 Km/hr](image3)

**3.1.3 Decelerating flow**

The inlet velocity is set to 60 Km/hr, while a 30 Km/hr initial guess is imposed on the exit velocity.

![Fig.6 Vin=60 Km/hr, Vout= 30 Km/hr](image4)
3.2 Model verification
For purposes of verifying the finite element model results, several video clips recorded for the road were studied for the coordinates of the path of two cars as a function of time, i.e. $x(t)$ and $y(t)$, then a cubic order polynomial was fitted between the points, as seen in Figure 7. This polynomial was differentiated to obtain the speed in the x-direction, plotted in Figure 8. The figure also contains a superimposed simulation result that can be best reflected by the accelerating velocity profile of Figure 4.

$$y = 1 \times 10^{-5}x^3 - 0.0019x^2 + 0.047x + 2.1739$$

4. Discussion
4.1 Velocity profiles
This section discusses the results obtained by running the three simulation conditions discussed above for the fully developed (full density), two-lane flow velocity conditions:

4.1.1 Accelerating flow
This is the case shown in Figure 4, where the flow has three high-speed patches of over 24 m/s (84 Km/hr) range. Since the flow is allowed to accelerate with the initial assumption at the exit velocity, which is set to the street speed limit, cars can attain such high velocities with no subsequent congestion. The aforementioned high speed patches are separated by corresponding relatively slow patches, also shown in the figure. The length of these patches varies according to the value of the relaxation factor, $\tau$, in equation (2) depending on the reaction time of the driver. The chosen value of $\tau$ is chosen to be 1 second, as recommended by [5].

4.1.2 Homogeneous flow
This is the case where the speed of the vehicular flow is not changed, where the inlet velocity of 60 Km/hr equals the 60 Km/hr initial guess exit velocity. It is noticed from the simulation results in Figure 5 that the flow speeds up right after the contraction of the geometry lined by a boundary layer that agrees with the imposed no-slip condition on the walls. This creates a central high-speed band that starts to slow down until it forces cars to exit at a velocity lower than the initial guess velocity of 60 Km/hr (around 41 Km/hr). The possible maximum attainable velocity for this case is 108 Km/hr as shown by the red band in the figure. This value cannot be maintained due to the tendency of drivers to slow down to velocities close to the speed limit even if the road conditions permitted higher velocities.

4.1.3 Decelerating flow
This is the final case studied, where the inlet velocity is set to 60 Km/hr, while a 30 Km/hr initial guess is imposed on the exit velocity, indicating a deceleration of the flow, or an accumulation of the cars within the solution domain in the case of a traffic jam. It is observed that the maximum speed occurs at the nozzle (geometry contraction) area with a velocity of around 83 Km/hr. This, however, does not last deep into the geometry as the allowable speed falls to around 19 Km/hr at the exit. This is expected to produce a shockwave that will travel upstream and cause the allowable velocities for the flow to slow down according to the pattern described by [4].

4.2 Model verification
Observations on the actual road was made by captured using a video camera that followed the road condition, especially during morning and drive back rush hours. Figure 7 shows experimental car positions as a function of time, and the cubic polynomial fitted is differentiated in Figure 8 and the simulation for the corresponding case of accelerating flow is superimposed on it. The figure shows good qualitative (accelerating) and
quantitative conformance with the calculated velocity values.

One interesting observation when the flow is well developed is that the vehicle velocities are large (equal to or more than 60 km/h) with equally high flow density. When the geometry is not choked, cars trying to merge into LANE1 will not have a chance to enter the lane and will have to continue their way down the tunnel through the tunnel lane (that is not included as the solution domain). This is simulated as a recirculation of the flow (as seen in the velocity profile in Figure 2) where the simulation was carried out by imposing a high inlet velocity that caused that prohibited cars not taking the proper lane (LANE1) early on from merging into the flow.

This is evident from observing the actual flow at the street, where at instants when the flow was smooth, cars could not find an opening because of the high density and were forced to carry on to the tunnel, as seen from the sequence of Figure 3.

5 Conclusions and future work

Finite element simulation of traffic flow for a busy street in Amman, Jordan is constructed and used to aid in predicting traffic patterns in a specified road geometry. The simulation imposed an incompressibility condition since no collisions between cars were permitted, which enabled to analogy of car flow to fluid flow in a pipe. The model showed an acceptable degree of conformance to actual observations, which can be extended in the future to include cases when the traffic density is lower than the maximum vehicular density of 45 cars per simulation area. Also, the simulation will be run for cases that have an added lane to the simulation to study the effect of the increased available area on velocity profiles.

References:


