Congestion costs incurred on Indian Roads: A case study for New Delhi

Neema Davis, Harry Raymond Joseph, Gaurav Raina, Krishna Jagannathan
Department of Electrical Engineering, Indian Institute of Technology Madras, Chennai 600 036
E-mail: {ee14d212, ee10b127, gaurav, krishnaj}@ee.iitm.ac.in

Abstract—We conduct a preliminary investigation into the levels of congestion in New Delhi, motivated by concerns due to rapidly growing vehicular congestion in Indian cities. First, we provide statistical evidence for the rising congestion levels on the roads of New Delhi from taxi GPS traces. Then, we estimate the economic costs of congestion in New Delhi. In particular, we estimate the marginal and the total costs of congestion. In calculating the marginal costs, we consider the following factors: (i) productivity loss, (ii) air pollution costs, and (iii) costs due to accidents. In calculating the total costs, in addition to the above factors, we also estimate the costs due to the wastage of fuel. We also project the associated costs due to productivity loss and air pollution till 2030. The projected traffic congestion costs for New Delhi comes around 14658 million US$/yr for the year 2030. The key takeaway from our current study is that costs due to productivity loss, particularly from buses, dominates the overall economic costs. Additionally, the expected increase in fuel wastage makes a strong case for intelligent traffic management systems.

Index Terms—road congestion, marginal cost, total cost, projections

I. INTRODUCTION
Traffic congestion in Indian cities is visibly on the rise. This has a detrimental effect on productivity, air pollution, fuel wastage, health, and quality of life. In the developed world, traffic congestion has long been recognized as an economic as well as a social impediment, and detailed studies on the economic aspects of congestion have been conducted. Such studies have been successful in sparking numerous policy deliberations, and have generated interest in devising novel traffic management systems.

A brief overview of road congestion statistics in some developed economies is given below.

- Annual congestion cost in the United Kingdom (UK) will reach 33.4 billion US$ by 2030, rising by over 50% from the 2014 levels of 20.5 billion US$ [2].
- Annual cost of congestion in the United States (US) as of 2014, has been pegged at 124 billion US$; this is projected to increase to 186 billion US$ by 2030 [2].
- In Australia, annual congestion cost levels are expected to rise from Australian Dollars (AUD) 3.5 billion (2005) to AUD 7.8 billion (2020) for Sydney, and AUD 3.0 billion (2005) to AUD 6.1 billion (2020) for Melbourne [8].

Such extensive studies have not been conducted for Indian cities as yet. However, it is being recognised that as India develops, congestion in cities is going to increase sharply, with numerous negative implications. The following statistics provide some insights into the congestion scenario in New Delhi:

- New Delhi’s vehicular population is projected to rise to 10 million by 2020, leading to a marked increase in congestion, which will severely impede economic activity [8].
- In New Delhi, at least about 300,000 US$ worth of fuel was being wasted everyday, by vehicles idling at traffic signals as early as in 1998 [27]. This figure jumped to approximately 1.6 million US$ per day as of 2010 [23].
- New Delhi has been named the world’s most polluted city among 1600 cities by the World Health Organisation (WHO), and vehicular emissions are a major contributor to this situation [31].

Most of the research in the literature studying economic aspects of congestion, uses the link-flow approach. An example of this is [23], which uses analytical models to establish congestion costs against a baseline scenario. Another related paper [14] uses a similar approach to estimate total traffic congestion costs. The approach followed by most of these researchers is to use an exponential congestion function, which relates the minutes needed to drive a kilometer in terms of the Passenger Car Units (PCU) in the city. We note that previous studies have not explicitly considered the effect of two-wheelers on the congestion costs. This may undermine the congestion estimates, as two-wheelers already outnumber cars, and will also increase in the future. The impact of two-wheelers has been incorporated in our study.

The main contributions of this paper are twofold. First, by analysing the average speed of GPS enabled taxis over a period of one year, we provide statistical evidence for the increasing congestion levels in New Delhi. Second, we quantify the macroeconomic cost of traffic congestion in New Delhi, due to a variety of factors [1].

We begin with an analysis of the GPS traces from taxis to empirically show a downward trend in the average vehicular speed over the year 2013. Specifically, we employ a statistical test, known as the Kolmogorov–Smirnov test, which indicates that the average vehicular speed is statistically lower in the first quarter of 2014, as compared to the first quarter of 2013. We posit that this reduction in average speed of taxis

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Increasing congestion levels include the following.

- People spend more time in traffic, leading to productivity losses.
- Vehicles spend more time idling, releasing more pollutants into the air.
- Increasing fuel wastages due to frequent traffic jams, and stalling at signals.

In order to quantify these losses, we conduct a macroeconomic analysis of road congestion. To that end, we first aim to understand the marginal external costs of congestion, which measures the additional cost incurred due to an additional PCU worth of traffic. This is estimated for three factors: namely, productivity losses, air pollution costs, and road accidents. We have also included some key inferences obtained by analysing the major air pollutants on the roads of New Delhi. Next, we derive estimates for the total costs of congestion. In addition to the previous factors considered, we also incorporate fuel wastage due to traffic delays in our computations.

Once the congestion costs are estimated, it is then reasonable to consider some cost projections based on historical trends. To that end, we project costs due to productivity losses and air pollution till the year 2030. A key finding of our study is that productivity losses incurred by bus commuters is the main contributing factor. This finding, coupled with the expected increase in fuel wastage, highlights the need for a combination of government policy and technology adoption. This work is an extended version of [18]. In addition to the work presented in [18], we have analysed taxi traces for the city of Delhi to provide evidence for the rising congestion levels. The marginal and the total costs are also elaborated on in this paper.

The rest of the paper is organised as follows. In Section II, the motivation for estimating the economic costs of congestion is provided, by analysing data. In Section III we compute the marginal costs of congestion, followed by Section IV, in which we compute the total costs of congestion. In Section V, we make projections on some of these costs based on vehicular growth projections. Finally, in Section VI, we present our conclusions and a few recommendations.

II. ANALYSIS OF TAXI TRACES

In this section, we provide statistical evidence for the rising congestion levels. In particular, we perform an analysis of vehicle speed, using taxi GPS traces. The GPS traces used here are provided by a leading mobile application based taxi service provider. The data contain the vehicular position in terms of latitude and longitude, the current speed, the taxi ID and the direction in which it is heading. These GPS traces are available for a period of over one year, from January 2013 to March 2014.

A prominent indicator of congestion in any city is the variation in average speed of vehicles over time. Observations show that for 78% of the time in January 2014, the taxis exhibited a lower speed compared to January 2013. Similarly for February 2014 and March 2014, the corresponding percentages were 86% and 71% respectively. In fact, in January 2013, around 22% of time, the speed was higher than the speed in January 2014 by 10%. See Table I for similar inferences regarding the three months of interest. The data was also plotted for visual clarity. A basic moving average filter was used to smoothen the data. Figure 1 compares the average smooth speed of taxis over the first 3 months of 2013 and 2014, i.e., over the months of January, February and March. We observe that there is a visible reduction in speed in 2014, as compared to 2013. While this effect is clearly visible in Figures 1a and 1b for a brief period in mid-March (see 1c), taxis travelled with better speeds in 2014. After aggregating the speed over each hour in the year of 2013, we used a linear regression model to fit the data. The fit resulted in a negative slope, indicating that the average speed reduced from 34.2 km/h to 33.6 km/h in the year 2013. When similar procedure was repeated for the number of taxis, we observed a fit with a positive slope. It shows an increase in the number of taxis by roughly 200 units. Even though not conclusive, we can safely assume that other vehicles such as two wheelers and buses will follow a qualitatively similar reduction in the average speed. The negative trend for average speed and the positive trend for the vehicle count suggest an increase in road congestion over the period of study.

Over the year 2013, vehicular speed on weekends was slightly lower than the speed on weekdays. This observation suggests that the roads in New Delhi suffer from more traffic jams on weekends than on weekdays. Apart from monitoring the average speed of vehicles, a similar congestion indicator
Figure 2: Number of taxis in various ranges of speed for the first 3 months of 2013 and 2014. There is a pronounced shift towards the lower speed ranges in 2014 compared to 2013.

(a) January 2013 versus January 2014
(b) February 2013 versus February 2014
(c) March 2013 versus March 2014

Table 1: Percentage reduction in speed in 2014 compared to 2013

| Fraction of time (%) | Reduction in speed (%) |
|----------------------|------------------------|
| Jan 48.7             | >5%                    |
| Feb 62.3             | >10%                   |
| Mar 48.2             | >20%                   |
| Jan 0.1              | >25%                   |
| Feb 0.16             |                       |
| Mar 0.12             |                       |
| Jan 0.031            |                       |
| Feb 0.1              |                       |
| Mar 0.042            |                       |
| Jan 0.009            |                       |
| Feb 0.013            |                       |
| Mar 0.011            |                       |

is the count of vehicles in different ranges of speed. In figure 2, we observe a shift in the count of vehicles towards lower speed ranges in 2014. This is evident in all the 3 months that we analysed. The number of vehicles having average speed > 40 has reduced marginally in an year. In the year 2014, the number of vehicles in the lower speed range (20-30 km/h) has increased, and in the higher speed range (30-40 km/h) has decreased as compared to 2013.

A. Kolmogorov-Smirnov test

In order to provide statistical evidence for the observations made by visual inspections, we conduct a statistical test known as the Kolmogorov-Smirnov test (K-S test) [7]. In the one sample variant of the K-S test, we test whether a specified test distribution could have generated the set of samples at hand. We are interested in the two-sample variant of the K-S test, which determines whether the two sets of samples differ significantly. The null hypothesis of the test states that the two sets of samples are drawn from the same distribution. We can reject the null hypothesis with high confidence if its p-value is close to zero. On the other hand, a larger p-value indicates that the two sets of samples are statistically more similar. The K-S statistic $D$ captures the distance between the empirical distribution functions of two samples.

We run the K-S test for the speed data obtained from taxi GPS traces. The samples are drawn from the first 3 months of the years 2013 and 2014. We first consider the null hypothesis that the Cumulative Distribution Function (CDF) of samples from 2013 is equal to the distribution function of samples from 2014. When the K-S test was performed for this null hypothesis, it resulted in a p-value of 2.2e-15 and a $D$ statistic of 0.2088. This gives us overwhelming confidence to reject the null hypothesis, and suggests that the samples from 2013 and 2014 are statistically quite different. Similarly, we could reject with high confidence that the underlying distribution corresponding to the 2013 samples lies above that of the 2014 samples. Finally, we obtained a p-value greater than 0.9 for the hypothesis that the underlying distribution corresponding to the 2013 samples lies below that of the 2014 samples. This provides statistical evidence that the average speeds in 2013 were indeed greater than those in 2014. The empirical distribution of the average speeds, plotted in Figure 3, is also consistent with the findings of the K-S test.

Thus, the preliminary data analysis using taxi GPS traces suggest that there is a downward trend in the vehicular speed for the period we analysed. The statistical test further suggests that there is a high probability that the two speed distributions from 2013 and 2014 are dissimilar, and that 2013 has a higher speed distribution compared to 2014 for the same observation period. These inferences point to a visible increase in traffic congestion in 2014, when compared to 2013.

We will now compute the losses due to congestion in terms of costs. For this, first, we calculate the marginal external costs of congestion and then, the total costs of congestion in the following sections.

III. MARGINAL EXTERNAL COSTS OF CONGESTION

The notion of marginal costs relates to the change in a dependent variable corresponding to a unit change in an underlying independent variable. In the case of transportation
systems, marginal costs of congestion refer to the costs incurred due to the addition of one vkm (vehicle kilometer) in an existing transportation network. Marginal costs indicate sensitivity of the transportation network to changes in demand. This in turn indicates the resilience of the transportation network [2].

An important distinction of marginal costs from similar measures is that marginal costs, in the case of road travel, almost always increase with the addition of a unit of demand. On the contrary, cost measures such as the average costs may reduce with increased demand due to economies of scale, scope or density in the supply of transport services [23]. Marginal costs are of great practical importance especially in congestion pricing schemes that are gaining widespread acceptance in several cities around the world [14]. For instance, [25] emphasizes the importance of marginal costs due to the close estimation of real transportation costs accrued.

Several approaches have been followed to compute the marginal costs of congestion. One of the earliest works, [39], computes the marginal costs by multiplying the per unit cost with the elasticity of the unit cost increased by one. The work makes use of traffic flow and velocity data collected by highway engineers, and lays emphasis on highway congestion. An important development in the computation of marginal costs is the inclusion of peak and off-peak loading as in [10]. Another important milestone in the study of marginal costs is [24] - it brings into purview the costs due to road damage and the subsequent increased costs due to vehicles operating on these damaged roads. A more recent work in the area of marginal costs is [20], in which the authors carry out an extensive study of the components making up marginal costs and their implications for policy purposes. The work closest to this section is [32], which computes the marginal costs in New Delhi with an elaborate methodology. However the work leaves out two important effects: two-wheelers and the effect of new legislation in New Delhi that has considerably reduced marginal costs due to air pollution [9].

To compute marginal costs, the first step is to understand the different components that contribute to the marginal costs. A non-exhaustive list of components considered so far is given in Table 2. The second step in computing marginal costs is to identify the components that are actually relevant. Ascertaining relevance of the components includes considering the geographical, legal and regional particulars, unique to the transportation network. For the purpose of computing the marginal costs in New Delhi, we consider only the following three components: productivity losses, environmental costs and accidents. The other costs are neglected for the following reasons:

- Infrastructure and maintenance costs are marginal in the case of New Delhi. Due to the developing nature of the Indian economy skilled labour is relatively cheaper [36], and hence implies reduced infrastructure costs.
- Operation and usage costs of vehicles, have been increasing globally. In the case of India, the effect of increasing operation and usage costs has been very gradual due to the increasing quality of infrastructure, and customer-facing technology [15].
- Additional service costs and Mohring effect can be neglected in the case of New Delhi, since state transportation schedules are not dynamic, and often times do not reflect the demand. Despite several studies highlighting the importance of a dynamic scheduling system for Indian cities, progress in its implementation is scarce and the schedules are more or less fixed [38].
- Fuel wastage is a relevant component for computing marginal costs in New Delhi. However, due to restricted availability of information, fuel wastage can only be considered as a component while computing total costs of congestion. It will be taken up in the next section.

The third step, is to examine the selected components individually and compute the marginal costs due to each of these components. The computational approach is similar to that found in [32], but with a few important modifications. The modifications include considering two-wheelers and taking into account the post legislation CNG bus policy.

From a total costs perspective, if $T_i$ is the total cost of congestion function, due to the $i^{th}$ contributing component. $\nu_C$, $\nu_f$ are the average vehicle speeds under congested and free-flow conditions respectively. Then, a plausible form for $T_i$ is:

$$T_i = F_i(\nu_C) - F_i(\nu_f). \quad (1)$$

Here, $F_i(\nu)$ is a function that represents total costs due to the $i^{th}$ contributing component when the average network speed is $\nu$. The derivative of total costs with respect to vkm is expected to directly give us the marginal costs. Note that the derivative of the second term in Equation (1) vanishes or leaves a very small contribution, depending on the network characteristics, since the average free-flow speed is constant. Hence, the marginal costs due to air pollution and accidents may be approximated to be the marginal costs of congestion due to air pollution and accidents. The following subsections compute the marginal costs due to each of the corresponding components. In the end, the total marginal costs due to all these contributions are computed.

A. Productivity Losses

Productivity losses are costs incurred due to delays experienced by commuters. The losses can be categorized into two dimensions:

| Category                        | Basis                                         |
|---------------------------------|-----------------------------------------------|
| Infrastructure maintenance      | Maintenance costs due to road usage           |
| Operation and usage             | Cost of an additional vkm                     |
| Productivity losses             | Cost due to delays                           |
| Additional service              | Cost due to providing remedial services       |
| Mohring effect                  | Benefits due to increased demand              |
| Accidents                       | Expected increase due to additional road travel |
| Emission and pollution          | Increased noise and emission costs            |
| Fuel wastage                    | Increased consumption costs                   |

Table 2: Components making up marginal costs [23]
A personal dimension that covers losses arising out of personal time forgone while stuck in traffic delays. It includes time, that could be used towards employment, rest or any personally gainful activity.

A commercial dimension, especially in the freight and cargo industry. Productivity losses may stem out of cancelled orders or refused shipments due to late delivery. While the first aspect that covers productivity losses has been widely studied, fewer works have taken up business impact caused by congestion [3]. We will stick with losses on a personal scale, since business impact of traffic congestion is difficult to be modeled for New Delhi.

To compute the productivity losses for an additional vkm, the first step is to specify a speed-flow relationship for a given mode, i at time j. We use the Passenger Car Units (PCU) metric in the speed-flow relationship as used in most works to capture the vehicle characteristics [32]. PCU is the impact that a transport mode has on traffic variables such as speed and it is compared against a car. For example, a motorcycle is considered as 0.5 PCU. A difference in our methodology is that we use PCUs for two-wheelers on Indian roads as investigated in [6]. The commonly used speed-flow relationship is given by:

$$t_{ij} = A_{ij}[A_2 + A_3 \exp(A_4q_i)].$$  \hspace{1cm} (2)

Here, $t_{ij}$ is the time (in minutes) needed to travel 1 km on mode $i$ during time interval $j$. $A_{ij}$, $A_2$, $A_3$ and $A_4$ are constants that depend on the characteristics of the transportation network under consideration. $A_{ij}$ also depends on the period of travel $j$, and $q_i$ represents the PCU of mode $i$. Note that this approach is justified at least in the case of New Delhi, since the speed-flow fit has a high $R^2$ measure [32].

The Marginal Economic Costs of Congestion due to Productivity loss (MECCPi) is thus given by:

$$MECCPi = \sum_j \partial t_{ij} / \partial q_i \times VOT_{ij}.$$  \hspace{1cm} (3)

In the above equation, $x_{ij}$ is the number of passenger kilometers (pkm) travelled in period $j$ by mode $i$. VOT$_{ij}$ is the Value Of Time for a user travelling in mode $i$, during period $j$. $\partial t_{ij} / \partial q_i$ is the increase in delay suffered in mode $i$ during period $j$, due to a unit increase in the PCU of mode $i$. Across modes, the value of time for commuters estimated in [32] is corrected to reflect present day price-levels by using:

$$P_{new} = P_{old} \Gamma_{2013} \left[ \frac{1}{1 + \frac{\text{inflation}_{2001} - 100}{100}} \right].$$  \hspace{1cm} (4)

where, $P_{old}$ is the original 2001 price (in Rupees per hour) used in [32] for the value of time for different modes of transport. $\Gamma_t$ is the price-level in New Delhi during the year $t$, and $i_t$ is the national inflation rate during year $t$. A textbook definition of price-level describes it as the sum of the prevailing prices of a standard basket of goods and services consumed indicating the prevailing value of money. Table 3 lists the value of time for passengers using different modes of transport. Comparing 2001 to 2013 levels (Table 4), a near doubling in the marginal costs due to productivity is observed.

### B. Air Pollution Costs

Vehicular emissions cause serious air pollution problems and are a health hazard. Air pollution costs arise from health and environmental damages due to vehicular emissions. Increased traffic congestion stalls vehicles and increases onroad time, which in turn considerably increases vehicular emissions. Computing marginal costs of congestion due to air pollution entails considerations such as emission per vehicle kilometer (vkm), vehicle fleet age structure, and the estimates of pollution costs per unit of the pollutant. The Marginal External Costs of Congestion due to Emissions (MECCPi) for a transport mode $i$, summed over all emitted pollutants indexed by $k$, is given by:

$$MECCPi = \sum_k \rho_i^k \delta_k.$$  \hspace{1cm} (5)

In the above equation, $\rho_i^k$ is the age-division-corrected emission structure for the $i^{th}$ mode, and $\delta_k$ is the cost per kilogram of pollutant $k$ emitted, computed in [53]. Further, $\rho_i^k$ is computed using:

$$\rho_i^k = \sum_j E_{ij}^k \gamma_{ij},$$  \hspace{1cm} (6)

where, $E_{ij}^k$ is the coefficient of emission per vkm for the $i^{th}$ mode of transport, belonging to the $j^{th}$ age-division, for the $k^{th}$ pollutant.

The emission coefficients are listed in Tables 5 [5] and 6 [6]. Though vehicular emissions consist of a large variety of GHGs (Green House Gases) as well as harmful pollutants, in this study we only consider pollutants that are emitted in significant amounts, such as: carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NOx), and Particulate Matter (PM). In Table 6 two differing sets of emission coefficients for PM are provided. The ‘Business As Usual’ (BAU) type corresponds to the PM emission coefficients, if the ruling to convert all buses to Compressed Natural Gas (CNG) had not been enforced in New Delhi. The next column in the table provides the most recent PM emission coefficients, following the ruling. Though the vehicle fleet-age structures differ, the PM emission coefficients are provided.
coefficients remain the same, since most older vehicles have been refit to comply with the existing standards.

The coefficient $\gamma_{ij}$, representing the distribution of vehicle fleet age structure, is given in Table 9 for New Delhi. Hence, using (4), (5) and (6), the marginal external costs of congestion due to air pollution can be readily computed; see Table 10.

We note that even for the newer buses from the 2006-2010 age group, there is an order of magnitude difference between the actual and BAU values for PM emission coefficients. For the older buses, the improvement in PM emissions can be as large as two orders of magnitude. This highlights the pivotal role and potential of government policy and enforcement in this area.

### C. Accidents

Accident costs arise mainly from factors such as manpower losses, vehicular damages, insurance and other exigency costs. Accident statistics for the year 2013 is as given in Table 11. The economic value of damages due to accidents has been assessed in [35]. In computing the cost due to accidents, the losses, vehicular damages, insurance and other exigency costs.

### D. Total Marginal Costs

Total marginal costs of congestion due to the three factors considered (productivity losses, air pollution, and accidents) are summed in Table 15. In Table 16 the contribution due to the air pollution component to the total marginal costs are compared against the results obtained by [32]. The key findings from these marginal cost estimates are as follows:

- The most significant increase in marginal costs is for cars, estimated at nearly 57%. In contrast, the corresponding figure for buses is only 10.4%.
- A striking observation is the decrease in the marginal costs due to air pollution in 2013. The contribution of the air pollution component has reduced despite the increased cost per gram of emissions corrected to the 2010 prices.

This appears to be a direct consequence of government

### Table 5: Emission coefficient $E_{ij}^{E}$ for cars in New Delhi (in gm/km) [32], [1]

| Age Group | CO   | HC   | NOX  | PM  |
|-----------|------|------|------|-----|
| 1991-1995 | 4.75 | 0.84 | 0.95 | 0.06|
| 1996-2000 | 4.53 | 0.66 | 0.75 | 0.06|
| 2001-2005 | 3.01 | 0.19 | 0.12 | 0.05|
| 2006-2010 | 0.84 | 0.12 | 0.09 | 0.03|

### Table 6: Emission coefficient $E_{ij}^{E}$ for buses in New Delhi (in gm/km) [1], [30]

| Age Group | CO   | HC   | NOX  | PM  | BAU | Actual |
|-----------|------|------|------|-----|-----|--------|
| 1991-1995 | 13.06| 2.40 | 11.24| 2.013| 0.032|
| 1996-2000 | 4.48 | 1.46 | 15.25| 1.213| 0.032|
| 2001-2005 | 3.97 | 0.26 | 6.77 | 1.075| 0.032|
| 2006-2010 | 3.92 | 0.16 | 6.53 | 0.300| 0.032|

### Table 7: Emission coefficient $E_{ij}^{E}$ for two-wheelers in New Delhi (in gm/km) [1]

| Pollutant | High Estimate | Low Estimate |
|-----------|---------------|--------------|
| CO        | 0.46          | 0.03         |
| HC        | 0.73          | 0.00         |
| NOX       | 108.26        | 7.37         |
| PM        | 869.57        | 63.73        |

### Table 8: High and Low cost estimates of $\delta^k$ (in INR/kg) for New Delhi [33]

| Age Group | CO   | HC   | NOX  | PM  | PM (BAU) | PM (Actual) |
|-----------|------|------|------|-----|----------|-------------|
| 1991-1995 | 13.06| 2.40 | 11.24| 2.013| 0.032    |             |
| 1996-2000 | 4.48 | 1.46 | 15.25| 1.213| 0.032    |             |
| 2001-2005 | 3.97 | 0.26 | 6.77 | 1.075| 0.032    |             |
| 2006-2010 | 3.92 | 0.16 | 6.53 | 0.300| 0.032    |             |

### Table 9: Vehicle fleet age structure $\gamma_{ij}$ for vehicles operating in New Delhi [1]

### Table 10: Marginal external costs of congestion due to air pollution

\[ MECCA_i = \sum \epsilon_{ij} H_i \frac{365}{\Psi_i \mu_i}. \]

In the above equation, $\epsilon_{ij}$ is the number of accidents in the $i^{th}$ serious category for the $j^{th}$ mode as in Table 11. Table 12 gives $H_i$, the average cost of the accident corresponding to the particular mode and the seriousness category. $\Psi_i$ is the average total number of trips in a day as given in Table 13 and $\mu_i$ is the average length of a trip for mode $i$ as in Table 14.

### Table 11: Accident statistics for New Delhi, $\epsilon_{ij}$ [33]

### Table 12: Economic costs of accidents, $H_i$ [35]
Distance GBP 7 billion in the UK 1.58 N / A 0.27 - 2.74 0.113 0.11 1.78 0.04 Lost Time Pollution Total [32] US$ 20.5 billion in the UK 1.78 GBP 18 billion in the UK Accidents 2.14 77571669 32735914 Total 32605073 0.12 0.12 GBP 71 million in 10 areas of Scotland 9.12 - 14.14 0.042 0.26 Marginal Cost (in INR/vkm) GBP 24 billion in the UK US$ 124 billion in the US 6.29 22.52 Marginal costs from [32]

Table 13: Average vkm per day commuted in New Delhi, $\psi_i \mu_i$ (in km/day) [29]

| Mode of Transport | Marginal Cost (in INR/vkm) |
|--------------------|---------------------------|
| Bus                | 1.578                     |
| Car                | 0.042                     |
| Two-wheeler        | 0.113                     |

Table 14: Marginal external costs of congestion due to accidents

policy: (i) the switch to CNG buses, and (ii) the complete phasing out of vehicles purchased before 1990.

IV. TOTAL COSTS OF CONGESTION

The total costs of congestion are the sum of all costs accrued due to the delays experienced arising out of stalled speeds caused by road traffic congestion. In most cases, the total costs of congestion are defined with respect to a baseline scenario where congestion is minimal. The excess costs over and above the operating points of this scenario are considered as the total costs of congestion [23]. This popular approach highlights the dependence of total costs of congestion on not only the number of vehicles, but also the transportation network aspects such as capacity.

Table [17] provides estimates of total costs of congestion made by several works for several transportation networks around the world. One aspect is clear, the cost has been consistently rising. Note that the costs of congestion computed by these works, correspond to the price levels when the research was actually published.

As we compute the total costs of congestion in the proceeding sections, it is also important to understand some issues regarding the total costs of congestion. Several authors have in the past questioned the meaning of the total costs of congestion. Some of the criticisms are:

- The ‘total cost of congestion’ is rather a misnomer. If the total costs of congestion are incurred due to congestion, does alleviating congestion guarantee that the economy will be better off by an amount equal to the total costs of congestion? Certainly not. Alleviating congestion implies infrastructural spending, which has to be meted out by the state [12].
  - Several paradoxes relating to transportation networks have proved that reducing congestion implies reducing travel impedance and hence increasing travel demand. Increased travel will only increase the total costs of congestion [12].
  - The total costs of congestion measures are also criticized because the baseline scenario is rather arbitrary. Accuracy of measures of average free-flow speeds have been questioned [12].

Despite questions raised on the utility and accuracy of total costs of congestion, such a measure is important in the case of a developing country like India. Some of the reasons for this are:

- India does not have an established system of basic infrastructure. For instance, metro transportation is yet to be opened in most of the cities. Expenditure on these facilities will considerably debunk congestion, while in the case of developed countries with already existing transportation facilities, increased expenditure may only marginally provide relief.
- Total costs provide an excellent direction for a country like India which is still in the planning phases. Cities are still being built - not the case in developed countries.

Total costs of congestion have been well-studied in the past. Though there are several variations in the computation process, the basic framework remains the same in all past works: compare the congestion scenario with a reference baseline scenario with minimal congestion. The earliest work, perhaps, on the total costs of congestion is [11]. The approach followed in the computation makes use of the basic delay aspect. However, [11] neglects the value of non-work time. In [24], the authors provide a different approach by categorizing road users and then computing a nationwide total cost figure for the UK. This approach has been criticized in [7] on dimensional counts, for multiplying marginal costs with a total volume. In [7], the authors use a link-based methodology to estimate time and operating costs, and then compare costs at free-flow and current speeds. In our approach, we study total costs of congestion by aggregating costs for the three
factors considered: productivity losses, air pollution costs and accidents. An additional cost considered in the case of total costs is the fuel wastage costs. All these costs are computed by comparing against a baseline scenario, mainly in terms of average speeds.

Though by definition a simple numerical integration of the marginal cost function seems to intuitively provide the total costs of congestion, the computation of the marginal cost function throughout the range of the integral is cumbersome due to changes in parameters $A_{ij}$, $A_2$, $A_3$ and $A_4$ in (2) as the number of vehicles change. Therefore, a data driven approach is adopted, that considers the prevailing averages of the various parameters that have been considered in the previous section.

The following subsections delve into the computational details of the total costs of congestion. We will first consider the contribution by productivity losses to the total costs, and followed by this, air pollution costs will be studied. Costs due to accidents follow, finally ending with the contribution of fuel wastage to the total costs.

A. Productivity Losses

Here, the productivity losses entail a total approach, i.e., losses incurred by all commuters due to delays caused by all vehicles in the network. An important point worth mentioning here is that, the productivity losses in this case will depend on the average vehicle occupancy. The reason for dependency on occupancy is that the costs in this case are not with respect to a vehicular parameter (such as vkm), but necessitate the inclusion of an aggregate passenger number to compute losses.

Computing the total costs of congestion due to productivity losses involves considering several factors. These include: Value of time, average occupancy, trip length by mode, number of trips by mode, free-flow speed and average speed in congested conditions. Computing most of these factors at an individual micro-level is a formidable task. So for the purpose of these computations, averaged values of these factors are available, and are expected to produce similar results. Considering these factors, the Total Costs of Congestion due to Productivity Losses (TCCPL) is then given by:

$$TCCPL = 365 \sum_i VOT_i \Psi_i \mu_i \Lambda_i \left( \frac{1}{\nu_C} - \frac{1}{\nu_f} \right).$$  \hspace{1cm} (8)

In the above equation, $\Psi_i$ is the average total number of trips in a day for mode $i$, $\mu_i$ (in kilometres) is the average length of a trip for mode $i$, and $\Lambda_i$ is the average occupancy for mode $i$. $VOT_i$ (in Rupees per hour) is the value of time for the commuter travelling in mode $i$, $\nu_C$ is the average speed in New Delhi under congested conditions, and $\nu_f$ is the free-flow speed of traffic. Both $\Psi_i$ and $\mu_i$ are provided in Table 13. Notice that, in New Delhi, the number of trips by buses is more than twice that for cars and two-wheelers. This is intuitive, since most cars and two-wheelers serve individual travel needs, and may be used just for commuting from home to work. However in the case of buses, they are in use almost throughout the day because of the scheduled public transportation trips. Just by looking at this table, one can come to the conclusion that whatever legislation is to be passed, favoring buses might have an overwhelming positive effect.

The average trip size, $\mu_i$ remains almost the same for all the three categories at around 10-11 km/trip. Fewer number of trips for cars and two-wheelers outlines the enormous potential that ride-sharing and similar initiatives can have, especially in the case of cars, where average occupancy is mostly less than 50%. While potentials for improvement and reducing costs exist in all the three categories, it must be observed that bringing about improvements in bus systems is considerably easier since most buses are state-owned. In the case of two-wheelers and cars, coordination among a large number of commuters may be essential, before being able to bring about considerable improvements.

In equation (8), $\Lambda_i$ represents the average occupancy for mode $i$. The average occupancy for buses is among the lowest in several similar works. For instance, [34] uses an occupancy rate as high as 85%, which translates to roughly an average occupancy of 34 in a 40-seater bus. This is an important point to note since taking higher average occupancies may considerably increase productivity loss costs. The free-flow speed ($\nu_f$) is taken to be 40 km/h as in [37], and $\nu_C$ is taken to be 22.2 km/h as in [29].

With (8) and Table 18, the total costs of congestion due to productivity losses are readily computed, and are listed in Table 19. Throughout this study we have used the exchange rate of 1 US$ = 60 INR (Indian Rupee). From the Table 20 cars contribute more than 10% of the total productivity loss. As the number of cars is projected to grow rapidly, there could be a severe detrimental effect not only on the car passengers, but on all the other road users as well. Also note that the productivity losses for buses are the highest, because of its higher occupancy compared to other modes of transport. This is a good area for policy-makers to focus.

B. Air Pollution Costs

The computation of total congestion costs due to air pollution follows a comparison approach against the free-flow scenario. The factors considered to compute air pollution costs are similar to those introduced in the previous section. An important factor to be considered is the correction factor, that

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**Table 18: Trips per day in New Delhi** [29]

| Mode     | Trips per day | Occupancy | Trip Size (km) |
|----------|---------------|-----------|----------------|
| Car      | 2902120       | 2.2       | 11.28          |
| Bus      | 7276892       | 20.0      | 10.66          |
| Two-wheeler | 3250755   | 1.2       | 10.03          |

**Table 19: Total costs of congestion in New Delhi due to productivity losses**

| Mode     | Cost (in million US$/Yr) |
|----------|--------------------------|
| Car      | 809                      |
| Bus      | 6310                     |
| Two-wheeler | 237           |
| Total    | 7410                     |
must provide an appropriate comparison with the baseline scenario. The correction factor must preferably be in terms of \( \nu_C \) and \( \nu_f \), since these are already available. Keeping these in mind, the Total Cost of Congestion due to vehicular Emission of air pollutants, TCCE is given by:

\[
TCCE = 365 \left( \frac{\nu_f}{\nu_C} - 1 \right) \sum_{k} \left( \Psi_{i_k} \left( \sum_{k} \rho_{i_k} \delta^k \right) \right). \tag{9}
\]

In the above equation, the inner summation with respect to the \( k \text{th} \) pollutant provides cost due to pollutants (CO, HC, NO\(_X\) and PM) emitted per vkm for the \( i \text{th} \) mode. This data is obtained from Tables 5, 6, 7, 8, and 9. Once this cost has been computed for the \( i \text{th} \) mode for all pollutants, the outer summation seeks to compute the total costs for all modes, throughout the year. Product of the cost of emissions per vkm with the average total vkm traversed per day \( (\Psi_{i} \mu_{i}) \) will give cost of emissions per day, for the \( i \text{th} \) mode. The outer summation over all modes, gives the Total Cost of Congestion due to Emissions (TCCE).

Note that in expression (9), we introduce a correction factor, which was not present in (8). This factor accounts for the reduced speed due to congestion. The basic assumption underlying the correction factor is that the pollutants emitted increase proportionally with the increase in travel time. This is only an approximation since in most cases, the emission characteristics and constituents change as the vehicle speeds change. The changes are cumbersome and difficult to model. Keeping the assumption, the fractional change in time on road due to congestion is:

\[
\text{Correction Factor} = \left( \frac{T_C - T_f}{T_f} \right), \tag{10}
\]

where \( T_C \) is the time taken by a commuter to travel a given distance in congested conditions and \( T_f \) is the time taken to travel the same distance in free-flow conditions. Since distances are the same in both congested and free-flow conditions, we have:

\[
T_C\nu_C = T_f\nu_f. \tag{11}
\]

Using the above and simplifying, we have:

\[
\text{Correction Factor} = \left( \frac{\nu_f}{\nu_C} - 1 \right). \tag{12}
\]

This is a rather simplified approach to computing the correction factor. More accuracy may be obtained by including travel demand elasticities [13], since increased congestion increases travel impedance, reducing demand for travel. Then, the following must hold:

\[
T_C\nu_C = \Pi_{TD} T_f\nu_f, \tag{13}
\]

where \( \Pi_{TD} < 1 \) is a factor to account for the reduced travel demand. Due to data unavailability and complexity in computing elasticities, we will use (11) instead of the slightly more accurate (13). The correction factor is hence equal to the fractional increase in travel time due to congestion. Using

| Mode       | Cost (in million US$/Yr) |
|------------|--------------------------|
| Car        | 41                       |
| Bus        | 670                      |
| Two-wheeler| 19                       |
| Total      | 730                      |

Table 20: Total costs of congestion in New Delhi due to emission of air pollutants

\[ \text{(11)}, \text{the total costs of congestion due to air pollution is given in Table 20} \]

C. Accidents

As in the previous section, in which we compute the marginal costs due to accidents, we see in this section that accidents contribute a less significant component to total costs. However, in this case, the total costs due to accidents includes an aggregate total cost incurred due to accidental events involving a range of seriousness levels. Computing the total costs of congestion is slightly more direct than computing the marginal costs of congestion due to accidents because the data available is already in an aggregate form. In the previous section we found the cost per vkm only after finding the total costs. Then, the Total Cost of Congestion due to Accidents (TCCA) is given by:

\[
\text{TCCA} = \left( \frac{\nu_f}{\nu_C} - 1 \right) \sum_{i} \sum_{l} \epsilon_{il} H_l. \tag{14}
\]

We also include the correction factor introduced in (9). The form of the correction factor, follows the underlying assumption that increased road-time increases the probability of meeting with an accident. However, note that in this case the elasticities of travel demand will not come into play. We assume, and with reason, that travel time does not have elastic dependencies - a commuter who can complete his travel sooner, will not stay on road, just to ensure that the entire time he expected to be on the road elapses. The treatment of elasticities is far more complex in this case. Additionally, some studies have also found that commuters prefer constant travel time over varying travel times, where commuters may actually end up saving time on some days [17].

The total cost due to accidents is provided in Table 21. The year-wise breakup of the number of accidents, as obtained from [8], is enumerated in Table 22. Note that the number of accidents is largely stable in the years 2008 through 2013. Accidents do not seem to follow any increasing or decreasing trend with observable parameters. Also, we notice that fatal accidents contribute to most of the costs. Thus, there is a compelling case to formulate and enforce very strict safety norms, that reduce fatalities in road accidents.

D. Fuel Wastage

Fuel wastage due to traffic delays leads to losses that can be traced directly to traffic congestion. Some of the reasons for this fuel wastage due to congestion include:

- Stalling at traffic signals.
### Summary of Total Costs

In this subsection, we present the total costs of congestion, having considered the various components that contribute to the total costs of congestion. Table 23 shows the total cost of congestion in New Delhi per year, with most of the data used to compute the contributions of the underlying factors falling in the range of 2008-2010. In INR terms, traffic congestion costed New Delhi close to 54,000 crores of Rupees in the year 2013. There are a few important points that are to be emphasised as evident from Table 23:

- Buses are the largest contributors to the total costs of congestion. But, considering the number of trips per day that buses in New Delhi undertake and the number of commuters whose travel demands they satisfy, buses are probably the most efficient transportation means, in terms of total costs.

- Costs due to productivity losses are the largest contributor to the total costs of congestion. All other factors fall within 10% of the contribution made by costs due to productivity losses.

- The contributions by cars to congestion costs is almost a billion US$/yr and given the occupancy of less than 50% these costs are likely to have the most potential for reduction.

### Cost Projections for Productivity Losses and Air Pollution

In Section II, we computed the marginal costs of congestion, followed by total costs of congestion in Section III. An important requirement now is to be able to approximately tell how these costs are expected to change with time. This is an essential requirement since it justifies recommended infrastructural spending to ease congestion.

This section provides the cost projections for the marginal and total costs until 2030. The closest work relating to the results in this section is [15], which uses projections to determine the optimal transportation mix. In our case, we use the projected vehicle population growth to determine both marginal and total costs of congestion and in turn, make projections on these costs.

Of the four underlying factors that have been considered as contributors to total costs of congestion, we argue that two of the factors - fuel wastage costs and accident costs may be neglected. Projections will then be made for the productivity losses and air pollution costs.

Accident costs are neglected in making the projections because:

- The number of accidents are difficult to be modelled and predicted. The number of accidents does not seem to show any strong dependence on the number of vehicles [8].
- Even if a method to accurately determine number of accidents was perfected, the contribution from such costs would be dwarfed by the total costs of congestion. For instance, in the present scenario, the contribution to the total costs from accidents is just about 0.72% of the total.

A similar situation is encountered in the case of marginal costs.

The fuel wastage costs are also neglected for the following reasons:

- The magnitude of fuel wastage costs is distorted due to changes in global oil prices. Projecting fuel wastage...
requires being able to project oil prices many years hence, which is an impossible task.  

- The dependence of fuel quantity wasted with the number of vehicles is non-trivial and may strongly depend on several factors such as infrastructure and other network characteristics of the transportation network.
- This is another minor contributor to the total costs, presently contributing less than 8% of the total costs and can hence be neglected.

Projections of marginal and total costs of congestion are made by obtaining the growth projections of the two underlying factors affecting these costs - productivity losses and air pollution costs. However, making projections directly based on these two factors is non-trivial. A good approach would be to find a common dependence on which both these two factors depend, and for which plenty of past data is available so as to make the statistical projections meaningful. Vehicular population is one such common dependence and it satisfies the past data availability criteria also.

There are advantages in making projections for productivity losses and vehicular emissions indirectly based on the projections for vehicle population, rather than directly making projections based on the individual factors:

- In the indirect approach, the projections are independent of the model used to arrive at the contributions made by productivity loss and vehicular emissions based costs.
- Another inherent advantage is that projections on the vehicular population of New Delhi have been widely studied; however, this is not true of the individual factors.

Note that this approach lacks accuracy, as with increasing vehicular populations, network parameters describing the network characteristics may well change. Though the approach underestimates the projected costs, it will serve to justify minimal infrastructural spending. The projections for vehicular population in New Delhi is completed using a spreadsheet model. This completes the first step of the projection process.

The next task is to model the dependence between vehicular population and the two most relevant underlying factors making up marginal and total costs. The equations below capture the dependence of these two factors on vehicle population. From (2), the dependence of Productivity Loss Costs (PLC) on the vehicle population, \( N \), is:

\[
\text{PLC} \propto e^{A_1N}. \quad (15)
\]

Similarly, since the Vehicular Emission Costs (VEC) depend on the number of vehicles, assuming an equal distribution and a similar modal share throughout the projected years, we have:

\[
\text{VEC} \propto N. \quad (16)
\]

The projections for vehicular population in New Delhi obtained from the simple spreadsheet model are provided in Table 24. Using Table 24 and equations (15,16), the projections for the marginal costs of congestion are as in Table 25. Similarly, projections for the total costs of congestion are given in Table 26.

### VI. Conclusions and Recommendations

The key takeaways from our study are summarised below.

- After monitoring the taxi GPS traces on the roads of New Delhi for a period of over an year, we noticed that there is a negative trend in the average taxi speed. We also observed a positive trend in the number of taxis during the same period of study. These patterns point towards the increasing levels of congestion in the city.

### Table 24: Vehicular population projections in New Delhi

| Year | Two-wheeler | Car | Bus |
|------|-------------|-----|-----|
| 2015 | 4918777     | 2512234 | 64748 |
| 2018 | 5608980     | 2885110 | 74713 |
| 2020 | 6035646     | 3127639 | 84643 |
| 2023 | 6634911     | 3461118 | 89259 |
| 2025 | 7013511     | 3693622 | 93971 |
| 2027 | 7402890     | 3908506 | 99580 |
| 2030 | 8050609     | 4236245 | 109330 |

### Table 25: Cost projections - marginal costs of congestion (INR/km)

An assumption regarding the projection for buses is that the government will continue sanctioning buses in line with the demands of the population, and will not look to increase bus frequencies so as to lower average occupancies. This is only a slight underestimation, since with increasing living standards in India, it is highly likely that buses will be sanctioned at a higher rate than predicted. Though this effect will not affect the productivity loss costs (which depends only on the number of passengers), it will increase the environmental costs due to the lower average occupancies, and hence increased vkm per day. This will once again underestimate the cost projections.

An alarming observation based on the projections is the nearly 70% increase in the number of cars. Clearly, this will not be sustainable, and will have a damaging impact, particularly on productivity losses, environmental costs, and fuel wastage.

### Table 26: Cost projections - total costs of congestion (million US$/yr)

| Year | Car | Bus | Two-wheeler | Total |
|------|-----|-----|-------------|-------|
| 2015 | 1033 | 7233 | 331 | 8597 |
| 2018 | 1288 | 7746 | 493 | 9527 |
| 2020 | 1486 | 8282 | 630 | 10398 |
| 2023 | 1809 | 8540 | 896 | 11245 |
| 2025 | 2074 | 8889 | 120 | 12015 |
| 2027 | 2354 | 9138 | 1410 | 12902 |
| 2030 | 2857 | 9731 | 2070 | 14658 |
The results from the K-S test suggest that the speed distributions for the years 2013 and 2014 are dissimilar, and that the taxi speeds are statistically higher in 2013. The reduction in speed in 2014 may lead to more productivity losses, pollution losses and fuel wastages, compared to 2013. Hence, it is very likely that the total congestion costs in 2014, and the subsequent years, will be higher than that in 2013. This supports the cost projections in Table 26.

Even 15 years after the authors’ claim in [19], buses still are the most popular means of road transport catering to about 60% of New Delhi’s total demand. The state-owned New Delhi Transport Corporation buses are in fact the largest CNG-driven fleet in the world [27]. It is clear from our study that buses are contributing a substantial portion of the total costs, primarily due to productivity losses. The productivity loss due to congestion delays of commuters who use buses accounts for about 75% of total costs of congestion.

Idling at traffic lights, signalised intersections and busy junctions due to congestion causes fuel wastage, which is another source of substantial costs. With the number of cars projected to increase sharply, this component is expected to play an increasingly significant role.

From Table 25, we see that the projected marginal congestion costs of cars approach that of buses. This means that in the year 2030, according to our projections, the cost of adding a vkm of car travel to the existing traffic network is very similar to the cost of adding a vkm of bus travel to the same network, despite the enormous differences in size and hence in road space occupancy. This goes to show that the New Delhi traffic network will be so saturated that the addition of one vkm of bus or car will be viewed similarly.

Another important conclusion is that cars have the most potential for cost savings, due to two important reasons: average occupancies not exceeding 50% and a low number of average trips per day. Ride-sharing and similar arrangements in New Delhi will have tremendous potential in terms of cost saving as well as easing congestion.

The economic costs arising from accidents is not a significant proportion of the total costs. Though accidents entail significant and irrevocable personal losses, their contribution is less significant from a macroeconomic perspective.

Based on the results obtained so far and the conclusions above, we provide some key recommendations to address the issues identified.

- The Government should look into setting up dedicated bus lanes. This would considerably reduce the productivity losses for commuters who use buses, encouraging other private transport users to commute by buses due to the reduced transit time. Our study also adds strong credibility to various works in literature that make a case for dedicated lanes for buses in New Delhi [16, 31]. In order to make dedicated bus lanes effective, it would be important to have more frequent, and more comfortable buses. This could also help in shifting a fraction of the motorists to buses.
- Employ state-of-the-art scheduling policies for buses. There is also a case to be made for equipping public buses with GPS and making the data publicly available. This would enable real-time solutions and innovation to flourish. Though these recommendations entail additional spending on the part of the Government, public transport investments by the Government in New Delhi have had high returns, as is evident in the case of the New Delhi metro [22].
- As fuel wastage is expected to increase, it would be important to employ intelligent traffic management systems, including smart traffic lights. Such solutions could be extremely valuable in future smart cities, where it may be possible to install the required infrastructure in advance.
- Car pooling and other similar measures must be promoted, and the Government should help facilitate and incentivise such practices where ever possible.

With regards to future work, a more comprehensive study on all the aspects that impact costs of congestion in New Delhi is certainly required. There are several aspects of this study, especially in the computational modelling aspects that can be extended. Some of these among several others are:

- Include travel demand elasticities to obtain a more accurate correction factor in [11].
- Compute the new δc costs for New Delhi. The existing costs are fairly outdated, last computed for the year 1998 using the transfer of benefit method as used in [33].
- Projections can be made more accurately, by considering parametric changes that are influenced by the vehicular population. The present approach makes projections based on vehicular growth projections, but assumes all else to be constant, hence underestimating the cost projections.
- Recompute the fitting parameters $A_1$, $A_2$, $A_3$ and $A_4$ obtained from [32]. The parameters are expected to have slightly changed now, due to the passage of time since they were first computed using curve-fitting methods in 2010.

The advantages of replicating similar systematic study in other major Indian cities can be clearly seen. Such studies would better inform cost-benefit considerations for the numerous possible solutions that may be considered, towards providing a smarter transportation infrastructure in various cities, which is an important requirement in the developing world.

| Policy Recommendation                  | Cost Impact    |
|----------------------------------------|----------------|
| Dedicated Bus Lanes                    | 6300 million US$/yr |
| Strict Vehicular Emission Control Norms| 730 million US$/yr |
| Safety and Accident Prevention Features| 65 million US$/yr |

Table 27: Policy recommendations and likely impact cost
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