ECONOMICS

Citywide effects of high-occupancy vehicle restrictions: Evidence from "three-in-one" in Jakarta

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Widespread use of single-occupancy cars often leads to traffic congestion. Using anonymized traffic speed data from Android phones collected through Google Maps, we investigated whether high-occupancy vehicle (HOV) policies can combat congestion. We studied Jakarta's "three-in-one" policy, which required all private cars on two major roads to carry at least three passengers during peak hours. After the policy was abruptly abandoned in April 2016, delays rose from 2.1 to 3.1 minutes per kilometer (min/km) in the morning peak and from 2.8 to 5.3 min/km in the evening peak. The lifting of the policy led to worse traffic throughout the city, even on roads that had never been restricted or at times when restrictions had never been in place. In short, we find that HOV policies can greatly improve traffic conditions.

Traffic congestion is a scourge of cities everywhere. In U.S. metropolitan areas such as New York, Washington, and Atlanta, people spend, on average, more than an hour a day commuting to and from work (*1*). In many developing countries, the figures are similar or even worse, with individuals spending on average 50 min per day commuting in Mumbai and more than 1.5 hours per day in São Paolo and Rio de Janeiro (*2*, *3*). In addition to wasted time, traffic congestion may influence urban economic activity, affecting important decisions from where to live to which jobs one would be willing to take. Moreover, it constitutes a substantial cause of health hazards from air pollution (*4*).

A commonly cited reason for congestion is the inefficiency of single-occupancy vehicles, which use a substantial amount of road capacity for each passenger transported. In response, one policy prescription is to restrict certain lanes or roads to vehicles carrying multiple passengers. First begun in the 1970s, so-called "high-occupancy vehicle" (HOV) lanes were introduced in Washington, New York, and California and have spread throughout metropolitan areas both in the United States and, somewhat, internationally (*5*).

Yet, the benefits of HOV restrictions are unclear, with this type of policy remaining quite controversial. The main concern is that HOV lanes are underused (*6*, *7*). By restricting certain lanes to HOV traffic, these policies reduce the amount of available road space available for regular, single-occupancy traffic. If not enough people are induced to carpool by the existence of the HOV lanes, these policies could potentially make traffic worse in the remaining lanes. They may also have spillovers, either positive or negative, on other routes, depending on how drivers change their routes in response to changes in congestion in the HOV lanes. The equilibrium traffic response from implementing the restrictions is difficult to predict theoretically because it depends on the full traffic network and the full network of drivers' origins, destinations, times of departure, and preferences. Indeed, the well-known Braess's Paradox states that adding more roads can actually increase equilibrium congestion (*8*), so what happens is ultimately an empirical question.

We examine this question empirically by analyzing the elimination of perhaps the most extreme HOV restrictions anywhere in the world: the "three-in-one" policy in Jakarta, Indonesia. This is an ideal setting to study traffic congestion policies. With a population of more than 30 million, Jakarta is the world's second-largest metropolitan area, second only to Tokyo (*9*, *10*). Virtually all commuters in the region use the roads in some form or another; the city has no subway or light-rail system and only a limited commuter rail network. Not surprisingly, it has some of the world's worst traffic: A recent study of cities using Global Positioning System data found that the typical Jakarta driver experienced an average of 33,240 "stops and starts" in traffic per year, the worst in the world. By this metric, traffic jams in Jakarta are more than twice as severe as the worst-ranking U.S. city, New York, where drivers average only 16,320 stops and starts (*11*).

Under the three-in-one policy, first introduced in 1992 and unchanged since 2004, all private cars during the morning rush (7:00 to 10:00 a.m.) and evening rush (4:30 to 7:00 p.m.) on the main streets of Jakarta's central business district (CBD) were restricted to those carrying at least three individuals. This included the 12-lane Jalan Sudirman, the city's main artery and home of the stock exchange, the education ministry, large shopping malls, and numerous corporate headquarters, as well as several other main thoroughfares (see Fig. 1). By requiring at least three individuals, the policy was more stringent than the common HOV2+ lane policies.

The policy was not necessarily popular, with many believing that it did little or nothing to help reduce Jakarta's notorious traffic (*12*). Although police were posted at the entrances of the three-in-one zone and routinely stopped cars in violation, with a maximum fine of Rp. 500,000 (~ USD 37.50), there was a potential workaround: The policy had led to the development of professional passengers, called "jockeys," who stood by the road near three-in-one access points and provided an additional passenger in exchange for around Rp. 15,000 (USD 1.20). In fact, a single driver in need of two additional passengers could hire a mother and child standing on the side of the road to gain another two bodies (*13*).

In this paper, we study the effects of the elimination of the three-in-one policy on traffic speeds throughout the city using innovative, high-resolution anonymized data collected from Android phones through Google Maps. On Tuesday, 29 March 2016, the Jakarta government unexpectedly announced the abolition of the three-in-one restrictions, effective 7 days later. They initially announced a 1-week trial; this was then extended for another month and then the policy was permanently scrapped on 10 May 2016. To study the impact of this change, starting two days after the first announcement (Thursday afternoon, 31 March), we began collecting real-time data on driving speeds on several main roads in Jakarta—including some roads affected by the three-in-one policies and alternate unaffected routes—by querying the Google Maps application programming interface (API) for each route every 10 min, 24 hours per day. This "live" data captures current travel conditions based on real-time reporting of traffic conditions from Android smartphone users and is intended for real-time navigation.

To study the effects, we rely on two alternative counterfactuals. First, we use preperiod data from the 2 to 3 days before the policy change took effect. Second, we take advantage of Google's own innovative prediction algorithms by asking Google to predict the expected trip duration for each route, day of the week, and departure time under typical traffic conditions. These predictions essentially use all of Google's data on average road speeds. We show that both counterfactuals are virtually identical.

We collected data in two phases. Starting on 31 March at 4:40 p.m. local time, about 48 hours after the announcement but 2.5 "weekday" days before the three-in-one policy was lifted, we began collecting traffic data in both directions on three main roads (see Fig. 1)—Jalan Sudirman, Jakarta's main artery and a road subject to the HOV policy, and two alternate roads that run parallel to parts of Jalan Sudirman that were never subject to the HOV policy: Jalan Rasuna Said (another main CBD road with many office towers) and Jalan Tentara Pelajar (an artery leading into the CBD from the southwest). Thus, we have data from both before and after the policy was lifted, as well as the predicted speeds described above. Starting on

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28 April 2016, we expanded our data set to include an additional previously HOV road, Jalan Gatot Subroto, as well as eight alternate routes that had never been subject to HOV restrictions that were suggested to us by the Jakarta Department of Transportation. As with the earlier roads, we also queried the "predicted" business-as-usual data for comparison. More details on the data can be found in the supplementary materials (*14*).

The data from before the policy was lifted reveal that traffic was clearly bad. We focused on delay, defined as the number of minutes to move one kilometer (i.e., delays are defined as the inverse of speed). Delays averaged 2.8 min/km on the former HOV road from 7:00 a.m. to 8:00 p.m. and 3.2 and 2.2 min/km on the two alternate roads (see table S1). Certain time intervals had considerably worse congestion, up to 3.6 and 4.4 min/km. By comparison, average delay is 0.7 min/km (53 mph) on the Los Angeles highways studied in Anderson (*15*). In Delhi, another congested city, delays are 2.6 to 2.7 min/km on average between 8:00 a.m. and 8:00 p.m. over many routes across the city (*16*).

The preperiod data also contains suggestive evidence that the HOV policy was effective in reducing traffic at the restricted times of the day. Specifically, on Jalan Sudirman, the delay was lower during the morning and evening peaks, relative to the midday off-peak and the hour after the evening peak, respectively. On the two nonrestricted roads, the opposite pattern holds. In fact, Jalan Sudirman traffic was abruptly worse right after the end of the two restricted time periods (fig. S1).

We begin our analysis of the lifting of the policy by comparing traffic right before and after the policy. In Fig. 2, we graph the average delay in minutes per kilometer on the weekdays for the former HOV road Jalan Sudirman (Fig. 2A), as well an alternate road, Jalan Rasuna Said (Fig. 2B); results for an additional alternate road, Jalan Tentara Pelajar, are in fig. S2. We average delay over both road directions (north and south) because there are strong traffic flows in both directions at both times (disaggregated results are in fig. S3). The dashed line denotes the preperiod days of 31 March (from 4:40 p.m. onward), 1 April, and 4 April, whereas the solid line denotes the postperiod from 5 April to 4 May. We started by examining only what occurred during the first month after the policy change so that our postperiod would be as comparable as possible to the preperiod. The concern is that factors—e.g., citywide changes in school schedules, income, and weather—may eventually change over time. We lift this restriction below to explore what happens over time. Bootstrapped 95% confidence bands, bootstrapped pointwise, and clustered by date and direction, are shown shaded. For convenience, vertical lines mark the morning and evening peak-hour intervals during which the three-in-one policy was in effect during the preperiod.

Traffic clearly increased after the HOV policy was lifted. On the former HOV road (Fig. 2A), we observed traffic increasing in both the morning and evening peak. This could be due to one of two factors: (i) after the abolition of the three-in-one policy, the number of car trips increased and there are more cars on the road (e.g., people stopped carpooling, stopped using bus transit, or increased their likelihood of travel to and from the CBD) or (ii) the number of cars on the road is the same, but people changed the times of day when they travel or their routes. Figure 2 shows that (ii) is unlikely to play a large role. If anything, we observe an increase in traffic on the former HOV road during nonpeak hours (Fig. 2A), especially after 7:00 p.m., when HOV restrictions were never in place.

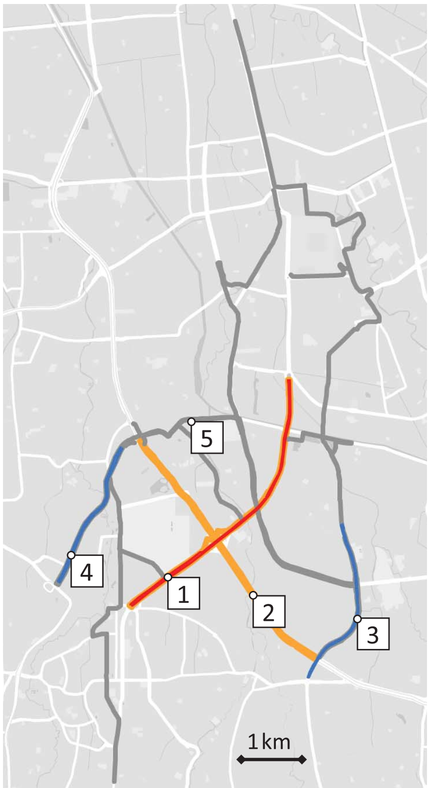

Fig. 1. Routes included in the analysis. (1) Former three-in-one road (Jalan Sudirman, red and orange). (2) Former three-in-one road (Jalan Gatot Subroto, orange). (3) Unrestricted alternate road (Jalan Rasuna Said, blue). (4) Unrestricted alternate road (Jalan Tentara Pelajar, blue). (5) Eight unrestricted alternate routes from the Jakarta Department of Transport (gray). Routes from the first phase of data collection are drawn with thin lines: 1 (red), 3 (blue), and 4 (blue). [Map data from Google, 2017]

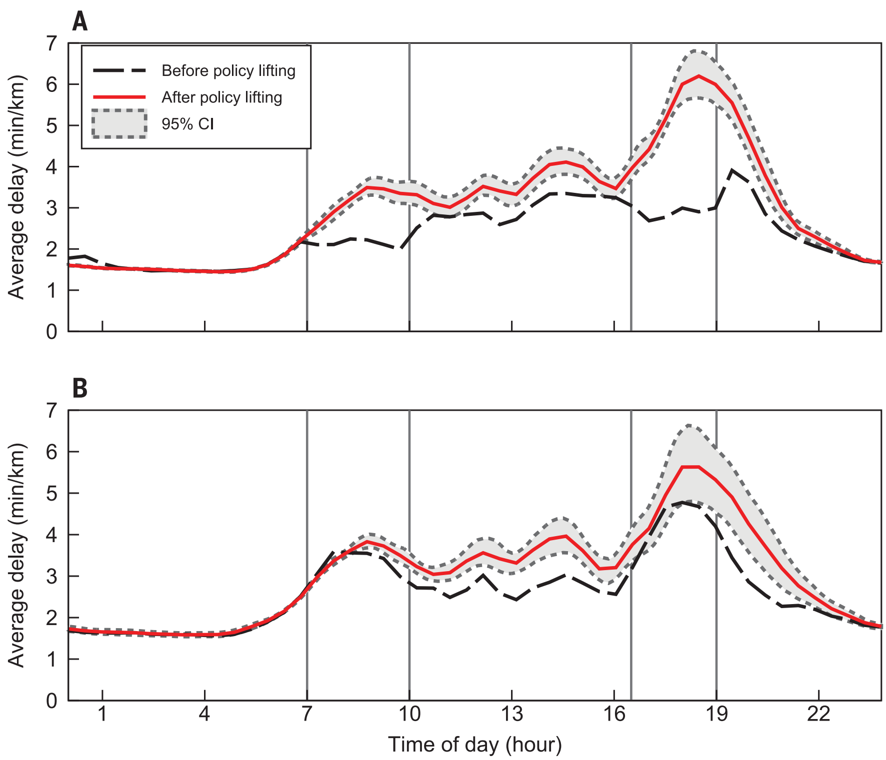

Fig. 2. Effect of three-in-one policy-lifting. (**A**) Former three-in-one restricted road (Jalan Sudirman) and (**B**) unrestricted alternate road (Jalan Rasuna Said). The graphs show locally linear regressions (Epanechnikov kernel, 0.2-hour bandwidth) of delay on departure time, before and after the lifting. Uses "live" data pre- and post-lifting. Predata are from Thursday 31 March (4:40 p.m. onward), Friday 1 April, and Monday 4 April. Postdata are from all weekdays 5 April to 4 May. For each departure time, there are two observations per route, corresponding to the two road directions. Pointwise bootstrapped 95% confidence bands around postdata, adjusted for date times road direction clusters (1000 bootstrap iterations).

Moreover, we do not observe any changes in traffic on the alternate routes in the morning peak hours and actually observe an increase in traffic on the alternate routes in the evening rush hour. This implies that individuals are not just changing their travel time or routes but rather that there is more traffic overall throughout the city.

Table 1 formalizes Fig. 2 and allows us to quantify the magnitudes. Specifically, we estimated, separately for each road segment and time period, the following equation

$$delay_{idh} = \alpha + \beta \times post_d + \gamma \times north_i + \varepsilon_{idh}$$

where $delay_{idh}$ is the average travel delay in minutes per kilometer for segment i on date d and for departure time h, $north_i$ is an indicator for whether segment i is northbound, and $post_d$ is an indicator for dates after the lifting. β is the coefficient of interest, providing the difference in average delays after the policy is lifted relative to before. Each column in Table 1 restricts the sample of departure times h. We provide β for both the morning (column 2) and evening rush hours (column 4) where three-in-one restrictions were in place in the preperiod, as well as the nonpeak periods (columns 1, 3, 5, and 6) that were always unrestricted on all roads. Standard errors are clustered by date times direction.

The results in Table 1 echo the graphical findings from Fig. 2. Table 1A shows that traffic is worse on the former HOV road after the policy is lifted. Specifically, we observe a 0.98 min/km increase (46% increase over the control mean of 2.14 min/km) in travel delay during the morning rush hour (significant at the 1% level, column 2) after the policy is lifted and a 2.5 min/km (87%) increase in the evening rush hour (significant at the 1% level, column 4). This translates into a decline in average morning rush hour speeds from 28 to 19 km/hour in the morning and a decline in evening rush hour speeds from 21 to 11 km/hour. The resulting speeds after the policy-lifting are extremely slow; by comparison, typical walking speeds are about 5 km/hour.

Perhaps more surprising, the elimination of the HOV restrictions during the morning and evening rush—from 7:00 to 10:00 a.m. and from

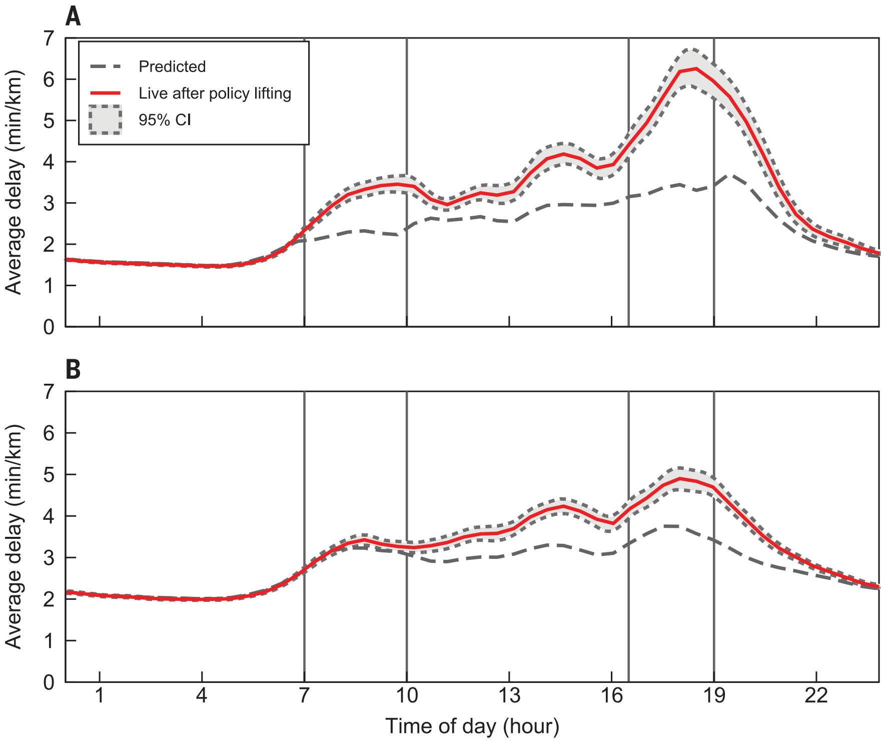

Fig. 3. Effect of three-in-one policy-lifting on expanded set of routes using "predicted" counterfactual. (**A**) Both former three-in-one restricted roads (Jalan Sudirman and Jalan Gatot Subroto) and (**B**) eight unrestricted alternate routes (identified by Jakarta Department of Transportation). Postdata from all weekdays 28 April to 3 June. See Fig. 2 for further information.

Table 1. Effect of three-in-one policy-lifting on restricted and unrestricted roads. Each column shows the policy effect in a given time interval. The outcome variable is delay (min/km) measured using "live" Google Maps API data. The sample is described in Fig. 2. The sample in each column is restricted to the departure time interval (open on the right) in the column header. For 31 March, data are available for the evening peak onward. Coefficients are from linear regressions of traffic delay (min/km) on post–policy-lifting and road direction indicators. Standard errors reported in parentheses are clustered at the date times road direction level. Significance levels: $*P < 0.10$; $**P < 0.05$; $***P < 0.01$.

	1	2	3	4	5	6
Time interval	**6:00 to 7:00 a.m.**	**7:00 to 10 a.m.**	**10 a.m. to 4:30 p.m.**	**4:30 to 7:00 p.m.**	**7:00 to 8:00 p.m.**	**8:00 p.m. to 6:00 a.m.**
(A) Delay on three-in-one road (Jalan Sudirman)						
Policy-lifting	−0.00	0.98***	0.55**	2.48***	1.98***	0.05
	(0.05)	(0.07)	(0.23)	(0.30)	(0.34)	(0.08)
Northbound	0.24***	0.12	−0.98***	−1.48***	−2.01***	−0.08
	(0.01)	(0.12)	(0.16)	(0.26)	(0.36)	(0.05)
Observations	264	792	1720	670	270	2656
Control mean	1.92	2.14	2.98	2.84	3.59	1.87
(B) Delay on alternate road (Jalan Rasuna Said)						
Policy-lifting	0.03	0.13	0.71***	0.60***	1.32***	0.16*
	(0.03)	(0.09)	(0.12)	(0.20)	(0.37)	(0.09)
Northbound	−0.08***	−0.14	−0.80***	−4.24***	−4.03***	−0.77***
	(0.02)	(0.09)	(0.17)	(0.21)	(0.33)	(0.07)
Observations	264	792	1720	670	270	2656
Control mean	2.19	3.34	2.71	4.35	3.61	1.89

4:30 to 7:00 p.m.—also led to increases in congestion at other times of the day when no HOV restrictions were in place in the preperiod. Specifically, traffic delays also increase by 2.0 min/km (55%) during the hour immediately after the evening peak (i.e., from 7:00 to 8:00 p.m.), which was never restricted, even during the HOV policy period. Likewise, traffic delay increases by 0.55 min/km during the midday period, which was also never restricted. This implies that individuals are not simply substituting away from travelling at other time periods once the three-in-one policy is lifted. We do not observe any change in traffic either in the hour before the morning rush hour (Table 1, column 1) or at night (Table 1, column 6).

We then turn to examine whether there were any positive or negative spillover effects of the HOV restrictions on other roads. One might expect that, after the elimination of the HOV restrictions, congestion should decrease on these alternate routes, because traffic induced to use these routes would revert back to Sudirman once it became open. Yet we find the opposite; delays on the main alternate route (Jalan Rasuna Said) also increase, by ~0.60 min/km (14%), during the evening commute. Delays also increase during the middle of the day and in the 7:00 to 8:00 p.m. evening period. We find broadly similar effects on Jalan Tentara Pelajar, another alternate route (see table S2). In short, these spillovers to other time periods and the alternative roads imply an overall negative general equilibrium effect on traffic congestion when the HOV policy is lifted, even at times or on routes that had previously not been affected by the policy.

We next extend the analysis in two ways: We explore (i) what happened to traffic over time, as individuals learned that traffic conditions worsened over time, and (ii) what was happening in the rest of the road network. For this analysis, we use the second phase of our data collection, adding another former three-in-one road and a larger set of eight alternate routes suggested by the Jakarta government. For these routes and dates, we do not have comparable pre–policy-lifting "live" data; instead, we rely on our second counterfactual, the Google Maps' predicted travel time data. The supplementary materials show, using a variety of checks, that this counterfactual appears reasonable; importantly, due to time lags and smoothing in their prediction algorithm, this predicted data does not take into account the change in policy.

Figure 3 graphs the live post–policy-lifting data against the predicted traffic data for the extended set of HOV roads (Fig. 3A) and alternate routes (Fig. 3B) for 28 April to 3 June. Table 2 provides the corresponding regressions. As before, we observed an increase in traffic for both the morning and evening rush hours for the former HOV roads after the policy is lifted; the evening rush hour delay is nearly 70% higher than the predicted delay (column 4 of Table 2A). We also observed both an increase in traffic in the non–rush hour times of the former HOV roads (Table 2A) and an increase in traffic on the alternate routes (Table 2B). In fact, the alternate routes experienced an increase in delay from 3.08 to 3.72 min/km (21% increase) in traffic delays in the midday period, an increase from 3.61 to 4.67 min/km (29% increase) in the evening rush hour, and an increase from 3.25 to 4.35 min/km (34% increase) in the hour after rush hour.

Examining the effects day by day, we found that the effect of the policy appeared immediately after the policy was lifted and persisted over time on both the HOV and alternate roads. Delay dropped during the holiday of Lebaran (when many Jakarta residents leave Jakarta to travel to their native regions) and increased again relative to the predicted after the holidays, albeit to a lesser extent (see figs. S4, S5, and S10 to S12).

There are several potential reasons why eliminating HOV restrictions could lead to a general equilibrium increase in congestion. The most parsimonious explanation is that more people were induced to drive; once people decided to drive during peak hours, they also used their cars at other times of day and on other roads, creating more traffic.

However, other explanations could explain our findings. For example, HOV restrictions may have prevented hypercongestion on the targeted roads. Hypercongested conditions describe a situation in which an increase in density of vehicles on the roads decreases average speeds by so much that the total flow of cars over the road actually falls (*17*). If eliminating the HOV restriction resulted in the emergence of hypercongestion on the affected roads, the total amount of volume handled by these roads would have fallen, forcing more traffic onto other roads and worsening speeds throughout the city (see the supplementary materials for a stylized example). Another potential reason is through the feeder aspect of the road network. It is possible that some people were trying to get to the now-congested CBD and that the congestion in the CBD spilled back to other parts of the network.

Although our data do not allow us to disentangle these hypotheses directly, the fact that we saw spillovers on other times of the day, and even on one alternate route that heads away from the CBD, suggests that there may have been more cars on the road.

Importantly, the magnitude of the policy effects is quite remarkable and considerably larger than those of other policies documented in the literature.

Table 2. Effect of three-in-one policy-lifting using "predicted" counterfactual. Each column shows the policy effect in a given time interval. The outcome variable is delay (min/km), measured using "live" or "predicted" Google Maps API data. The sample is described in Fig. 3. The sample in each column is restricted to the departure time interval (open on the right) in the column header. Coefficients are from linear regressions of traffic delay (min/km) on "live" and road direction indicators. Standard errors reported in parentheses are clustered at the date times road direction level. Significance levels: *P < 0.10; **P < 0.05; ***P < 0.01.

	1	2	3	4	5	6
Time interval	**6:00 to 7:00 a.m.**	**7:00 to 10:00 a.m.**	**10:00 a.m. to 4:30 p.m.**	**4:30 to 7:00 p.m.**	**7:00 to 8:00 p.m.**	**8:00 p.m. to 6:00 a.m.**
(A) Delay on former three-in-one roads (Jalan Sudirman and Jalan Gatot Subroto)						
Policy-lifting	–0.02	0.88***	0.81***	2.29***	1.98***	0.19***
	(0.02)	(0.08)	(0.10)	(0.19)	(0.21)	(0.04)
Northbound	0.18***	–0.09	–0.21	–0.75**	–1.08***	–0.18***
	(0.03)	(0.11)	(0.15)	(0.29)	(0.35)	(0.05)
Observations	384	1152	2494	960	384	3832
Control mean	1.93	2.23	2.75	3.31	3.63	1.83
(B) Delay on alternate routes (identified by Jakarta Department of Transportation)						
Policy-lifting	–0.02*	0.09*	0.64***	1.06***	1.10***	0.11***
	(0.01)	(0.05)	(0.09)	(0.12)	(0.10)	(0.02)
Northbound	0.28***	0.51***	0.71***	0.75***	0.35**	0.20***
	(0.01)	(0.06)	(0.09)	(0.18)	(0.16)	(0.03)
Observations	384	1152	2494	960	384	3832
Control mean	2.41	3.12	3.08	3.61	3.25	2.27

For example, in the 7:00 to 8:00 p.m. time period—when three-in-one was never in effect—we find that eliminating three-in-one led to increases of delays of 1.3 to 2 min/km, even on alternate roads. By contrast, estimates are that the London Congestion Charge led to a decrease in delay of 0.6 min/km (*18*). Anderson (*15*) found that a public transport strike in Los Angeles led to an increase of between 0.2 and 0.4 min of delay per mile during peak hours on highways throughout the city. Kreindler (*16*) studied the introduction of short-term driving restrictions based on license plate numbers in Delhi and, using similar Google Maps data, found an improvement of ~0.2 min/km across the city, and other studies of even-odd restrictions have found small effects due to household behavioral responses (*19*, *20*).

These relatively large effects are even more notable given the challenges of implementing HOV policies in a developing country. In particular, as discussed above, in Jakarta, there was a widespread practice of hiring "jockeys" to serve as extra passengers in order to enter the three-in-one restricted areas. Had the widespread use of jockeys compromised the policy, we would expect little or no effect of the lifting. The evidence emphatically rejects this view, because the lifting of three-in-one made a large difference to traffic congestion.

In sum, we show that the lifting of Jakarta's three-in-one policy not only had effects on traffic on former HOV roads but also had spillovers to alternative roads and time periods. The results therefore suggest that quantity restrictions on severely congested roads can have beneficial spillover effects on traffic throughout the city, whether by potentially eliminating hypercongestion or by getting cars off the road. We cannot decisively say, however, whether the three-in-one policy improved welfare. This depends on how commuters with cars value the alternatives to single-occupancy cars (e.g., carpooling, taxi, public transport, or not traveling). However, given the extremely high congestion levels, we can infer that the wedge between private and social cost is also high, making it likely that the equilibrium after the lifting is severely inefficient.

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ACKNOWLEDGMENTS

We thank D. Acemoglu, M. Anderson, A. Banerjee, and M. Turner for helpful comments; A. Yansyah, Jakarta Transportation Agency (Dishub) for technical advice; and M. Fryar, Z. Hitzig, W. Perdhani, and F. Siregar for helpful assistance. This project was financially supported by the Australian Government's Department of Foreign Affairs and Trade. All views expressed in the paper are those of the authors alone, and do not necessarily reflect the views of any of the institutions or individuals acknowledged here. All data and programs are available at http://dx.doi.org/10.7910/DVN/48U7GP.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/357/6346/89/suppl/DC1
Materials and Methods
Supplementary Text
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21 March 2017; accepted 25 May 2017
10.1126/science.aan2747

Science

Citywide effects of high-occupancy vehicle restrictions: Evidence from "three-in-one" in Jakarta

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Science **357** (6346), 89-93.
DOI: 10.1126/science.aan2747

How to make traffic worse everywhere

One policy aimed at improving traffic flows in large cities requires vehicles to carry two or three passengers, usually in lanes or roads set aside for high-occupancy vehicle (HOV) travel. Whether this actually increases speeds depends on how heavily the HOV roads are used and the availability of alternate routes. Hanna *et al.* took advantage of an abrupt policy change––the elimination of HOV rules––in Jakarta to collect the travel times from Google Maps for HOV and alternate routes before and after the change (see the Perspective by Anderson). They observed a serious worsening of traffic throughout the city.

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