1 Characterization of the Ozone Weekend Effect in California

1.4 The Weekday/Weekend Behavior of Ambient Ozone Concentrations in California

1.4.1 Abstract/summary

Since the 1970's, air quality studies have shown that ozone concentrations increase on weekends at many locations – the so-called “weekend effect”. Most of these studies have focused on a specific region, and many of the studies have used simple statistical approaches that fail to yield conclusive evidence in the presence of strong random noise. We analyze day-to-day changes in daily peak ozone concentrations for three major urban areas in California using a more precise statistical approach, estimating percentage changes from day to day and examining spatial patterns among sites. We filter out much of the nuisance variation and use robust statistics to reduce the effect of outliers. We find that many sites in all three areas exhibit a characteristic "weekend effect", but some sites show different patterns or fail to display a statistically significant pattern. Many sites show a "Sunday effect", an increase from Saturday to Sunday, in the 1996-98 period. Similar spatial patterns prevail in all three regions.

1.4.2 Introduction/background

Several studies have documented the phenomenon of higher ozone concentrations on weekends in California. This so-called "weekend effect" has aroused strong interest because of its potential implications for ozone control strategies. In the 1970's, some researchers found evidence for elevated ozone concentrations on weekend days at some locations in Southern California. Some analyses based on more recent data show that ozone concentrations continue to be higher on weekends, although ozone concentrations have decreased steadily over the last two decades in most areas of the state. Evidence from other parts of the United States varies, some areas exhibiting higher ozone values on weekdays, some failing to display a significant difference between days of the week, and others behaving similarly to Southern California.

Because most, if not all, previous studies have been limited to a single geographic area or a handful of scattered sites in several areas, it has not been possible to make inter-regional comparisons with a single, consistent methodology. While a few studies have taken a more sophisticated statistical approach, most have been based on simple measures such as the number of hours above a regulatory standard concentration or simple mean concentration by day of week. Since such techniques are relatively insensitive and do not fully take into account the statistical properties of the data, they do not yield precise estimates of the day-to-day changes in ozone concentration, and they may fail to detect subtle patterns against a background of strong random noise.

In this chapter, we summarize the work we detailed in a 1999 paper titled “A characterization of the weekday-weekend behavior of ambient ozone concentrations in

California." The complete paper is in Appendix. The goal there was to accurately characterize the weekend effect in three major urban regions of California: Los Angeles, the San Francisco Bay Area, and Sacramento. The analysis is based on consecutive or "sibling" days in terms of percent rather than absolute differences in concentration. Differences in absolute concentrations can be misleading when the base values are too large or too small. Hence, percents yield more precise estimates because they measure change in terms of the base values. We use analytical techniques tailored to the special characteristics of the data. The improved accuracy leads to a more reliable assessment of statistical significance. Finally, we use a graphical tool to examine spatial patterns among sites in each of the three. Section 1.4.4 presents a qualitative assessment of the results; numerical estimates of day-to-day differences for specific sites are tabulated in Table 2 of the Appendix.

1.4.3 Methodology

1.4.3.1 Data

We examined daily maximum one-hour average ozone concentrations at each site during the high ozone period, May 17 through October 15, from 1992 to 1998. The choice of the beginning and ending dates corresponds to the ozone season in California. Data were taken from the Air Resources Board ADAM air quality database. Due to the impact of the federal reformulated gasoline (RFG) and California cleaner-burning gasoline (CBG), we looked at the results for two separate periods, as shown below. RFG was introduced in Los Angeles beginning in the Spring of 1995, and CBG was introduced statewide (including Los Angeles) in the Spring of 1996. Data for 1995 were excluded for Los Angeles because, as a transition year, it was not expected to be representative of either period.

	Pre-RFG/CBG	Post-CBG
Los Angeles	1992-94	1996-98
San Francisco Bay Area	1992-95	1996-98
Sacramento	1992-95	1996-98

1.4.3.2 Methods

To characterize the variation in ozone concentrations over the week, we computed the average shift from one day of the week to the next. Since the magnitude of the systematic shift based on the day of the week is modest compared with the random variation from one day to the next, we tested whether the differences are statistically significant. Based on these average differences, we examined the sites in each geographic region as a group, to see whether sites that share topographical, meteorological, or emission characteristics show similar patterns of ozone changes throughout the week. We did not consider precursor or meteorological data in this study; we focused solely on ozone behavior. In the next few paragraphs we describe the specific steps in the analysis in greater detail.

1.4.3.3 Serial Dependence

One of the key features of air quality data is serial dependence, or the day-to-day correlation in data. Owing to the atmospheric persistence of ozone and its precursors, and the tendency for meteorological factors in ozone behavior to be similar from one day to the next, the peak ozone concentration is generally similar from one day to the next. Our interest is in studying the changes in ozone due to the day-of-week effect. Hence, we subtracted ozone values between consecutive days, hoping that in so doing, we have better isolated the day-to-day changes from the "noise" caused by sources common from one day to the next. Further, we examined only differences involving weekend days; i.e., we computed differences between Friday and Saturday, Saturday and Sunday, and Sunday and Monday, ending up with three differences for each week. Because ozone concentrations do not correlate well between weeks, we can treat these groups of three differences as statistically independent from one week to the next. This assumption of independence is necessary for significance testing.

1.4.3.4 Isolating the Weekend Effect from Other Sources of Variation

A series of daily ozone measurements exhibits several kinds of systematic variation, including meteorology, trend, and any day-of-week effect which may be present. We therefore took measures to filter out variation caused by factors other than the day-of-week effect and isolate the signal of interest. A typical series of daily peak one-hour average ozone concentrations would show the characteristic seasonal ozone cycle, with high concentrations in summer months and low concentrations in winter. It would also exhibit ozone concentrations that are more variable in the summer months; i.e., the variability scales with the concentration. Within the summer season itself, ozone values would also decline from year to year. Such downward trend could result from the introduction of CBG in 1996, an El Niño event during 1997-98, continued emission reductions, and vehicle fleet turnover. A weekend effect, if present, would appear as a periodic pattern embedded within all this variation. To isolate it, we applied several steps, including:

<u>Logarithmic transformation.</u> By taking natural logarithms of the original ozone concentrations, we render the variability approximately constant over time and independent of the ozone concentrations. Many air quality analyses use this technique to normalize the data distribution and enable more appropriate statistical tests.

<u>Smoothing and residuals.</u> We applied a smoothing filter to the log transformed concentrations. The output of the filter is a weighted moving average of the log transformed concentrations, where the weights assigned to each group of 29 values (for approximately one month) taper off to either side. In other words, the smoothing was done via averaging across 29 days, giving higher weights to days closer to the center of each group of values – a moving 29-day average. The result is a smoothed version of the input series, which captures the seasonality and trend components in the data but

smooths out the day-to-day variation. We subtracted this smoothed series from the log-transformed concentrations to obtain "adjusted daily peak ozone concentrations". The log-transformed ozone concentrations and smoothed series for Azusa are shown in Figure 1.4-1.

1.4.3.5 Restriction to Summer Weekends

At this stage, we restricted the data to summer weekends (Friday through Monday, May 17 through October 15), removed weekends on which a major holiday fell (Memorial Day, Independence Day, Labor Day), and computed successive differences from one day of the week to the next. Henceforth, these day-to-day differences will be referred to as “differences”. We ended up with three differences for each site, for each week of the study period. As a rough check, we also computed means of midweek differences, Tuesday minus Monday through Friday minus Thursday, and their standard errors. None proved significant at the 95% confidence level, for any site in any area, for either study period, indicating that there’s no significant day-of-week effect during the week.

1.4.3.6 Robust Estimation of Means

We can think of individual differences between days as being the sum of two components: the periodic signal we are interested in, and nuisance variation or "noise". If the noise component is random and symmetrically distributed, the arithmetic averages of the differences should provide a good estimate of the periodic signal. However, while the bulk of the data are distributed roughly in a normal, bell-shaped distribution in two dimensions, the data include occasional outlying values which can have a large influence on the mean concentration. Accordingly, rather than simply taking arithmetic means, we used a robust technique designed to reduce the effect of outliers, resulting in weighted means that downplay 5% of the data. Details of this technique are in the Appendix.

We tested the significance of each individual mean difference. The results are also shown in Table 2 of the Appendix. Although the robust technique we used down-weights outlying values conservatively, it has a tendency to underestimate the magnitudes of the variances. Therefore, there is a slight tendency to overestimate the significance level of the differences. Also note that the 95% level of significance stated in Table 2 of the Appendix applies to *each* individual difference; it is not a simultaneous confidence level for the entire set of differences.

1.4.3.7 Descriptive Statistics

In Table 2 of the Appendix, we report average percent changes in ozone values between days. These are computed from the robust mean differences by transforming the log values back into the original units.

We also report absolute differences, which are extrapolated from the mean Friday ozone using the percent changes computed above. These are intended merely to serve as a convenient standard for comparison and not as rigorous estimates, since our methods optimized the estimation of percent changes rather than absolute differences.

1.4.3.8 Graphical Analysis

To facilitate the interpretation of the spatial patterns among sites, we graphically displayed the results by performing a separate principal component analysis (PCA) on each geographical region. Treating the robust mean day-to-day differences in ozone for each site as the defining coordinates in three-dimensional space, PCA effectively rotates the coordinate axes in space so as to explain most of the variability in the data with the smallest number of variables. In the case of the average differences, three-dimensional plots clearly showed that for each region, the differences lay in a thin plane in three-dimensional space. Accordingly, we can use PCA to find a new set of coordinate axes lying within the plane of the data, and describe most of the variation in the data using only two variables. The results are useful as a visual tool, as they make clear which sites are behaving similarly, and what changes took place between the two periods. Figures 1.4-3 through 1.4-5 show plots of the data for the Los Angeles region in the transformed coordinate system; plots for other regions can be found in the Appendix. Mathematically, the principal components are linear combinations of the original coordinates. It turned out that the two new variables identified through PCA are indicators of the “weekend effect” and the “Sunday effect”, respectively; more will be explained later.

1.4.4 Results/discussion

Table 2 of the Appendix presents the mean Friday maximum ozone concentrations, day-to-day changes in percent and absolute concentrations, and an indication of whether the percent changes are significant at the 95% confidence level. Overall, the day-of-week effects vary from area to area. However, regardless of the region, ozone levels improved dramatically on both weekends and weekdays during the 1990’s.

In general, the percent changes from Friday to Saturday and from Sunday to Monday are significant for Los Angeles and the San Francisco Bay Area, but not for Sacramento. Since there are fewer sites in Sacramento, and many sites lack a substantial fraction of the data, we will focus our discussion on Los Angeles and the San Francisco Bay Area.

1.4.4.1 Los Angeles

During 1992-94, the typical pattern for ozone in many sites in Los Angeles is a large increase from Friday to Saturday, no change or a small decrease from Saturday to Sunday, then a large decrease from Sunday to Monday. This "weekend effect" is strongest at downtown sites and least pronounced at transport sites far downwind. For example, Table 2 of the Appendix shows that at the Los Angeles-North Main Street site (LA), adjusted daily maximum ozone increased 31% from Friday to Saturday, increased slightly (1%) on Sunday, then decreased 28% on Monday. Lynwood, Pasadena, and Pico Rivera, near Los Angeles, share a similar pattern. Further downwind, at Azusa and Glendora, the effect is not as strong; however, the Friday to Saturday and Sunday to Monday changes are statistically significant.

Generally speaking, the further downwind a site is, the milder the weekend effect. At the downwind extreme, Lake Gregory, Banning, Hemet, Perris and Santa Clarita show a relatively small weekend effect. In the 1992-94 period; the Friday to Saturday and Sunday to Monday changes are not significant. Lake Gregory actually displays a slight increase from Sunday to Monday. In fact, in the early period, Lake Gregory, Banning, and Hemet are characterized by a pattern of ozone behavior different from the "typical" weekday effect: a Friday to Saturday increase, a Saturday to Sunday decrease, and relatively little change from Sunday to Monday. However, in 1996-98, Lake Gregory shows a more typical weekend effect: a statistically significant increase from Friday to Saturday, and a significant decrease from Sunday to Monday. Banning, Hemet and Perris all closed or had insufficient data to be included in the second study period. Note that Sunday ozone averaged 35% higher than Friday in the urban core but only 13% higher at Santa Clarita and Lake Gregory. These sites are far “downwind” and at higher elevation than most sites in the basin.

Interestingly, the two coastal sites west of downtown Los Angeles, Hawthorne and West Los Angeles, behave similarly to the western San Bernardino County sites (Fontana, Upland, and San Bernardino) much farther downwind, exhibiting a mild weekend effect. A likely explanation is that at the two coastal sites, which experience steady westerly sea breezes during the high ozone season, ozone and precursors are blown downwind rapidly, so the effects of photochemical interactions mainly become visible further downwind.

Between the early period (1992-94) and the later period (1996-98), there are several noticeable changes in weekday-weekend behavior. During 1996-98, after the introduction of RFG/CBG, mean ozone concentrations decreased substantially on all days, regardless of the day of the week, at virtually all sites. Figure 1.4-2 illustrates the change at Azusa – overall decline across all days, with significant changes during the weekend. While the Friday to Saturday and Sunday to Monday changes remain significant, many sites begin to exhibit a "Sunday effect", a modest increase from Saturday to Sunday. Some downwind sites, including Azusa and Glendora, show a stronger weekend effect than in 1992-94.

The principal component plots for selected sites in Los Angeles (Figures 1.4-3 through 1.4-5) graphically display the patterns discussed above. The first principal component on the x-axis is an indicator of the overall weekend effect. Sites further to the right in the plot show a stronger weekend effect than those to the left, which show a relatively weaker effect. The second principal component on the y-axis represents a Sunday effect, or Saturday-to-Sunday increase, superimposed on the overall weekend effect. Sites further to the top show a stronger Sunday effect than those near the bottom of the graph. Figure 1.4-3 displays results of eight sites in 1992-94 while Figure 1.4-4 displays the same sites in 1996-98. Figure 1.4-5 combines the two previous figures and reflects the changes between the two periods. As it indicates, the general upward migration along the y-axis, going from the first period to the second, shows that many sites experience a stronger Sunday effect during the second period than in the first. Take Azusa, for example. The hollow marker for Azusa in the bottom of Figure 1.4-5 indicates a moderate weekend effect and very weak Sunday effect during 1992-94. However, the migration to its solid marker on the upper right portion of the plot indicates stronger weekend effect and higher Sunday effect as well during 1986-98.

1.4.4.2 San Francisco Bay Area

In addition to Los Angeles, Table 2 of the Appendix also displays results for the San Francisco Bay Area. During 1992-95, the typical pattern of the weekend ozone behavior is similar to that in Los Angeles: a large increase from Friday to Saturday, no change or small decrease from Saturday to Sunday, and a large decrease from Sunday to Monday. This weekend behavior is strongly evident at a cluster of urban sites including Oakland, San Leandro, and San Jose-4th Street (SJ 4th). As in Los Angeles, the transport sites far downwind show a milder weekend effect; the changes from Friday to Saturday and Sunday to Monday are not significant at the 95% level.

After the introduction of RFG/CBG, peak ozone concentrations dropped on all days of the week during 1996-98. The weekend effect becomes stronger at the three urban sites, but it remains largely unchanged at other sites. Many sites begin to exhibit a Sunday effect; all sites show a larger increase (or smaller decrease) from Saturday to Sunday in the later period. Note that Sunday ozone is 30% higher than Friday in the urban core but only 14% higher at Bethel Island, Fairfield, Gilroy, and Livermore. These sites are downwind receptors but are not considered “elevated” sites.

As in Los Angeles, far downwind sites in the San Francisco Bay Area do not show any significant day-to-day changes in ozone behavior. For example, at Bethel Island, Fairfield, and Napa, peak ozone does not change significantly during the weekend in either period.

1.4.4.3 Sacramento

The results for Sacramento, also in Table 2 of the Appendix, are less conclusive, partly due to lack of data. During 1992-95, two far downwind sites, Auburn and Folsom, behave like the downwind sites in Los Angeles and the San Francisco Bay Area. The lone downtown site, Sacramento-T Street (Sac T St), shows ozone behavior similar to the downtown sites in Los Angeles. Note that the increase from Friday to Saturday is significant only at three sites: North Highlands, Sacramento-Del Paso Manor (Sac DP), and Sacramento-T Street. At several sites, peak ozone actually increased slightly from Sunday to Monday. These sites are distinguished by an increase in peak ozone from Friday to Saturday, and a decrease from Saturday to Sunday, similar to the far downwind sites in Los Angeles during 1992-94.

During 1996-98, peak ozone concentrations dropped on all days of the week. While many sites show ozone increases from Saturday to Sunday, the changes during the week are almost all statistically insignificant.

1.4.5 Conclusions and implications

Generally speaking, in Los Angeles and the San Francisco Bay Area, the typical "weekend effect" behavior (increase on Saturday, flat or small decrease on Sunday, and decrease on Monday) is strongly evident at the downtown sites and less visible at the transport sites far downwind. While most sites exhibit little change from Saturday to Sunday during the earlier period, a Sunday effect (increase from Saturday to Sunday) becomes noticeable in the later period. In the later period, after the implementation of California CBG, ozone concentrations dropped substantially on all days of the week at virtually all sites included in the study. Except for some sites, all these patterns are prevalent in the three regions we studied, but results for Sacramento are less conclusive and revealing due to lack of data. One should note that, in spite of the general pattern, some of the sites displayed a pattern different from the "up on Saturday, flat on Sunday, down on Monday" pattern generally regarded as typical, or failed to exhibit a statistically significant weekend effect.

1.4.6 Recommendations

This analysis is purely descriptive, motivated by a desire to reduce a huge volume of data on ozone concentrations, spanning most of California and the better part of a decade, to a meaningful set of summary statistics and some useful broad qualitative conclusions. To make accurate judgements about causes and underlying mechanisms will require a careful approach which takes precursor concentrations, meteorology, and diurnal patterns explicitly into account – something not done in this analysis but addressed in other chapters of the report. We hope that the information presented in this analysis will yield insight into fruitful directions for further research on causation and provide facts against which to test possible explanations.

Figure 1.4-1. Natural logarithms of the daily maximum 1-hour ozone concentrations at Azusa are plotted for the 1994-97 period.
The smoothed data series is superimposed as a dark line.

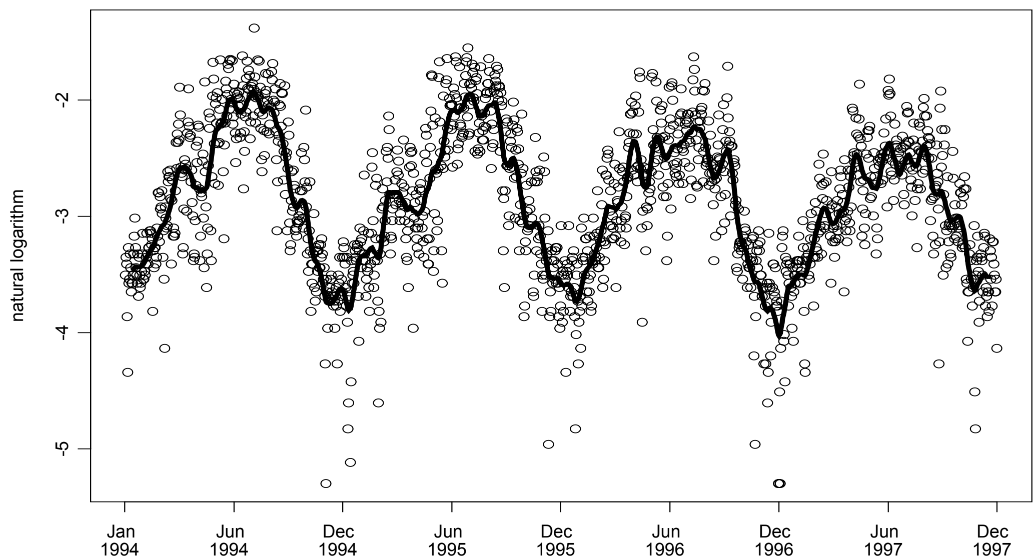


Figure 1.4-2. Mean peak ozone concentration by day of week at Azusa.

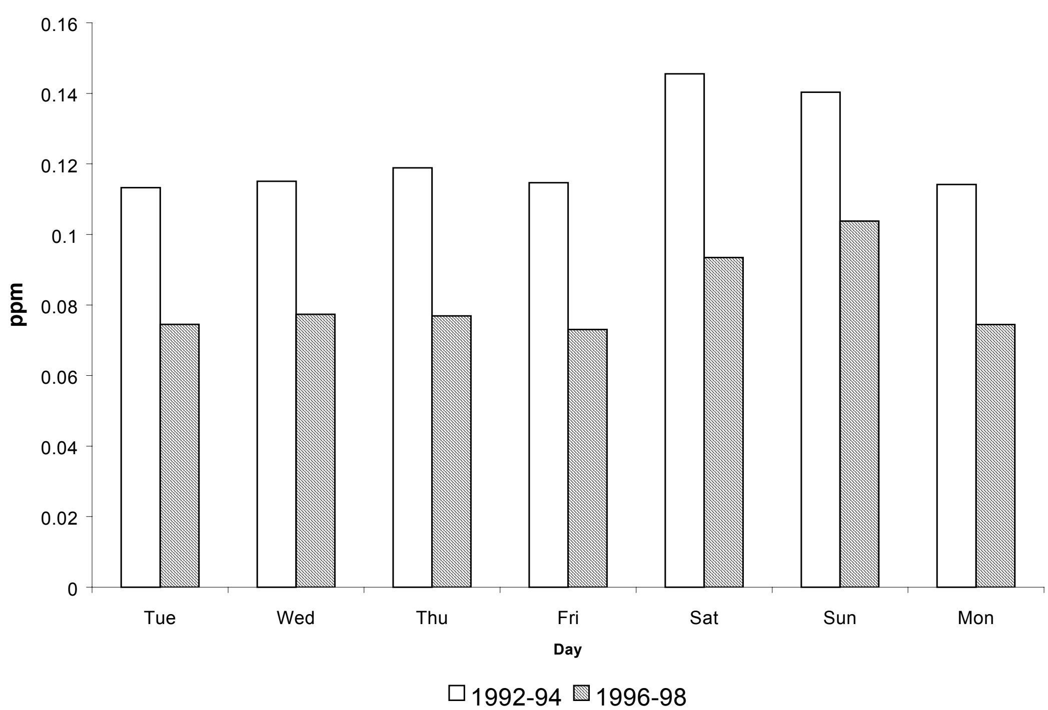


Figure 1.4-3. Principal component plot for selected sites in Los Angeles area, 1992-94.

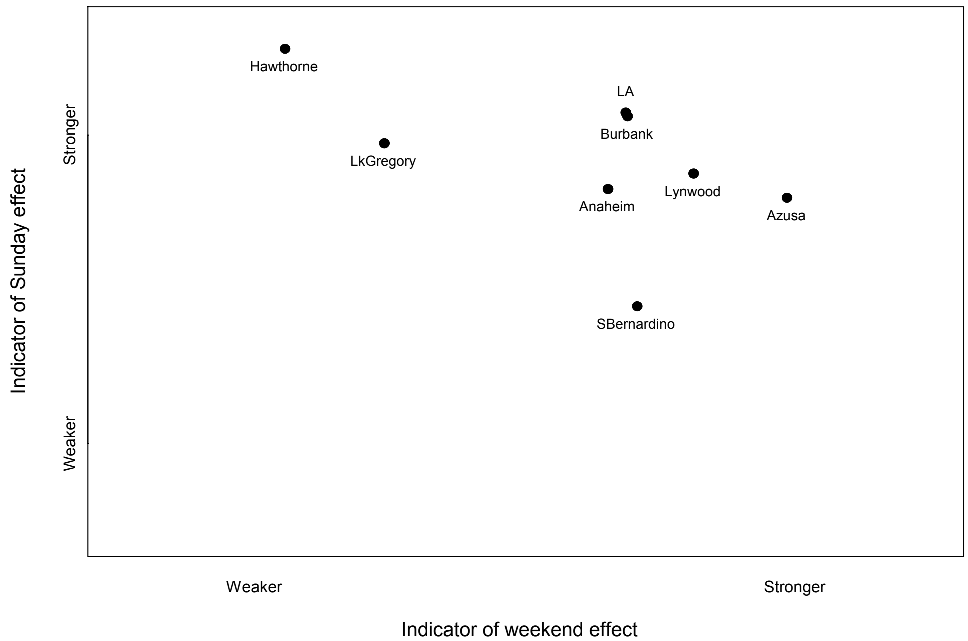


Figure 1.4-4. Principal component plot for selected sites in Los Angeles area, 1996-98.

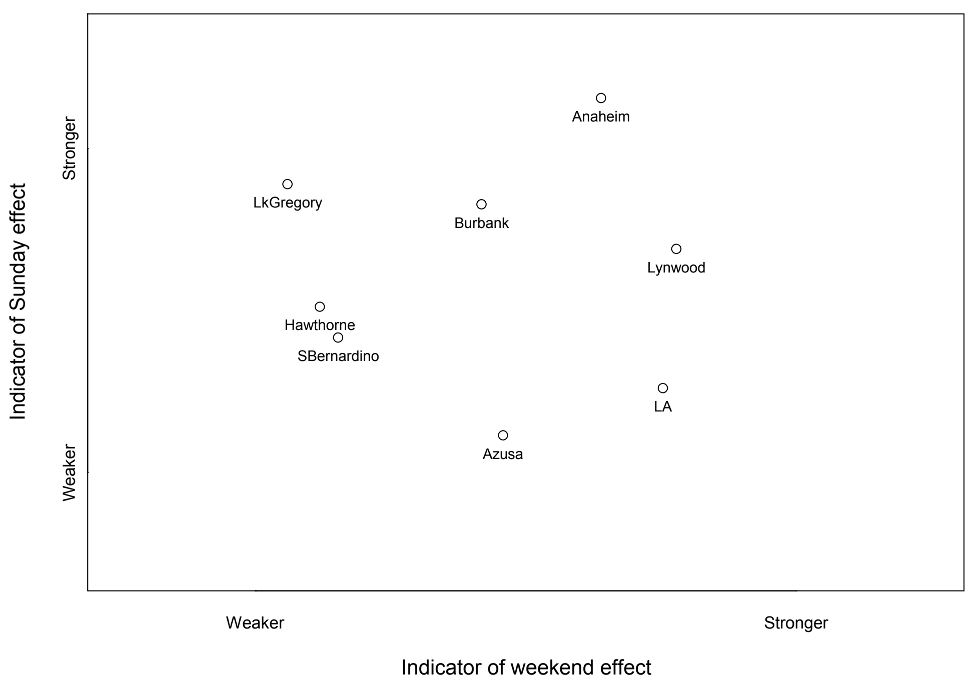
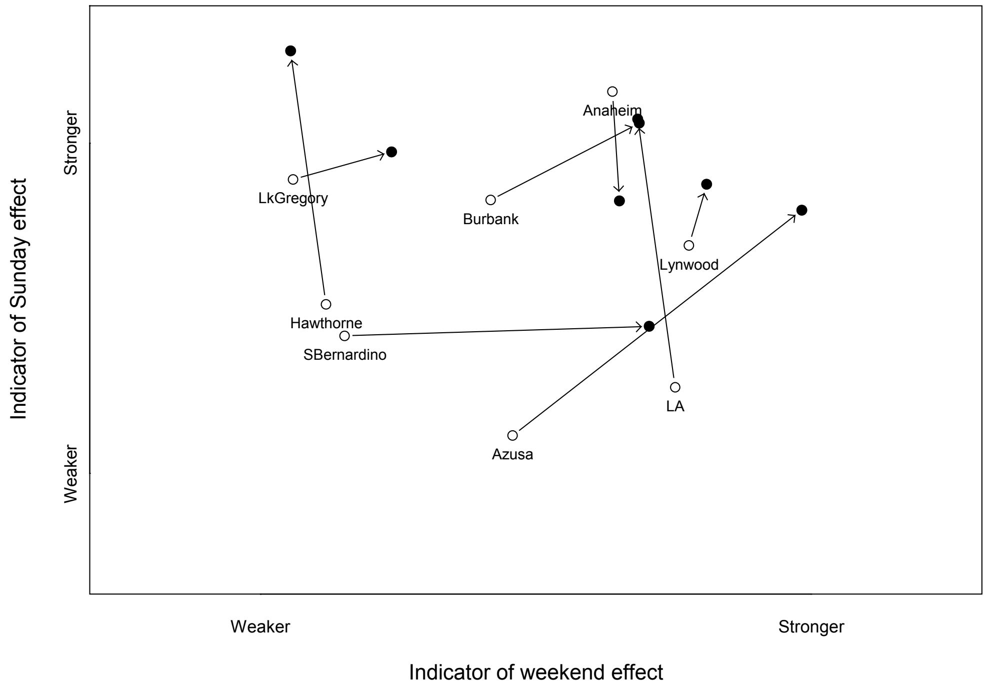


Figure 1.4-5. Principal component plot for selected sites in Los Angeles area, both periods. A migration to the upper-right direction indicates a stronger Sunday effect superimposed on a stronger weekend effect.



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