5 The effect of steric bulk on C–C bond activation

Inspired by:
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To be submitted

Abstract

We have studied the effect of steric bulk on the Pd, PdCl\textsuperscript{–} and Pd(PH\textsubscript{3})\textsubscript{2} catalyzed activation of prototypical alkane C–C bonds, including water solvent effects. Introducing methyl substituents on the C–C bond of ethane causes this bond to become weaker. The insertion of Pd(0) into the bonds, however, becomes more difficult and the reaction barrier increases. This increase is especially pronounced for the highest number of methyl substituents. We show that the rise in reaction barrier is a combination of two effects: 1) more methyl substituents make it more difficult for the palladium to approach the C–C bond, and 2) methyl substituents cause, via a higher σ*\textsubscript{C–C} LUMO energy, a decrease in back-donation from the metal to the C–C bond. These trends persist upon using Cl\textsuperscript{–} or (PH\textsubscript{3})\textsubscript{2} as ligands. Several aspects of the influence of these ligands on the reaction paths are also discussed. The effect of water as a solvent does not significantly alter the qualitative behavior of these reactions.
5.1 Introduction

The main aim of this chapter is to investigate changes in the transition state for the oxidative insertion (OxIn) of Pd(0) into the C–C bond of alkanes if we systematically increase the number of methyl group substituents on the ethane C–C bond. We investigate the central C–C bond in the series of ethane, propane, methylpropane, butane, dimethylpropane, and finally tetramethylbutane. So we start by adding methyl groups at one of the carbon atoms one at the time, until we have a tert-butyl group in dimethylpropane (butane has one methyl group on both carbon atoms). In the final step we add three methyl groups on the other carbon, which is then fully substituted on both sides. We want to see what effect this increased crowding of the central bond has on the reaction path. Specifically, we will show how the number of substituents influences both the height of the barrier and the position of that barrier along the reaction coordinate, the stretching of the C–C bond.

Besides assessing the effect of a bulky substrate on the intrinsic bare Pd(0) reactivity towards the central C–C bond, we are also interested in the effect of using different Pd catalysts. To this end, we also study the OxIn of PdCl− and Pd(PH3)2 complexes into the same C–C bonds. Both these aspects were of course covered in the preceding chapters, and some similarities will be seen.

5.2 Substrates

The substrates used in this study, ethane, propane, methylpropane, butane, dimethylpropane, and tetramethylbutane, are shown in Figure 5.1. The geometries of the catalysts used in this study can be found in Figure 5.1 as well. Homolytic bond dissociation enthalpies and bond lengths of the substrates can be found in Table 5.1.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>C–C (Å)</th>
<th>BLYP</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 H3C–CH3</td>
<td>1.541</td>
<td>83.2</td>
<td>90.1</td>
</tr>
<tr>
<td>2 H3C–CH2Me</td>
<td>1.541</td>
<td>79.8</td>
<td>89.0</td>
</tr>
<tr>
<td>3 H3C–CHMe2</td>
<td>1.544</td>
<td>76.4</td>
<td>88.6</td>
</tr>
<tr>
<td>4 H3C–CMe3</td>
<td>1.550</td>
<td>73.1</td>
<td>87.5</td>
</tr>
<tr>
<td>5 MeH2C–CH2Me</td>
<td>1.542</td>
<td>76.2</td>
<td>87.9</td>
</tr>
<tr>
<td>6 Me3C–CMe3</td>
<td>1.608</td>
<td>53.1</td>
<td>78.6</td>
</tr>
</tbody>
</table>

* In kcal mol⁻¹. † Bond length of central C–C bond. ‡ Experimental values taken from Blanksby and Ellison.138
The activated C–C bond becomes increasingly longer when adding the methyl substituents, going from 1.541 Å in ethane and 1.607 Å in tetramethylbutane. At the same time the bond weakens from 83.2 kcal mol\(^{-1}\) to 53.3 kcal mol\(^{-1}\). The inherent bond strengths of these bonds are expected to influence the reaction barrier.

Similar as in the previous chapter, we have performed a simple energy decomposition analysis to explain the observed trends in bond strengths (see also Table 5.1). Thus, we again take the equilibrium structures of the substrates and adjust, without optimization, the C–C bond length, and apply the energy decomposition analysis at each bond distance. Figure 5.2 shows the result of this analysis. The analysis supports what one would intuitively expect to happen for this series of bonds. As more sterically demanding methyl groups are added, the destabilizing Pauli repulsion increases, weakening the bond. The Pauli repulsion also becomes steeper for more crowded bonds, resulting in the longer equilibrium bond distances. It is clear from the analysis that the orbital and electrostatic interactions play a small, and even opposite, role to the Pauli repulsion that ultimately dictates the trend in bond strengths. The most sterically congested substrate, tetramethylbutane, not shown in Figure 5.2, experiences even higher Pauli repulsion, caus-

Figure 5.1 Geometries (in Å, deg) of the substrates and catalysts used in this study.

Figure 5.2 Energy decomposition analysis of the substrates as a function of C–C bond distance.
ing the very weak bond in that case. Of course, the similarities with the analogous analysis on the C–H bonds in chapter 4 is unmistakable.

5.3 Stationary points

First, we discuss the potential energy surfaces (PES) of our [Pd] + alkane reactions; the main results are presented in Table 5.2. The nomenclature used in the figures is as follows: the capital indicates the catalyst used, the number indicates the substrate used (see Figure 5.1) and the lower case letter indicates the stage of the reaction (Figure 5.3). For example, C2b means that catalyst C is used (Pd(PH3)2) together with the second substrate (2, propane), and the reaction is in stage 2 (b, the transition state).

Figure 5.3 Geometries (in Å, deg) at ZORA-BLYP/TZ2P of stationary points along the potential energy surface for the oxidative insertion reaction of Pd into the C–C bond of ethane (1), propane (2), methylpropane (3), dimethylpropane (4), butane (5) and tetramethylbutane (6).

The PES of the oxidative insertions consists of a reactant complex prior to the actual transition state. This reactant complex (RC) usually has the palladium coordinated in a η-fashion (weak bonding on the C–H moieties) to a methyl group. However, several minima associated with the reaction complexes can be found. Whenever an IRC calculation allowed us to find a specific RC, this is the one shown in Figure 5.3. Otherwise the RC is found by a geometry optimization starting from a transition state ge-
ometry, slightly distorted along its normal mode. In general, the RCs found for different substrates are close in energy. The Pd(PH$_3$)$_2$ complex does not show an appreciable RC, there is only a very weak interaction of around -1 kcal mol$^{-1}$ at a distance of over 4 Å between palladium and the C–C bond. The insertion of the Pd complex then continues via a central barrier after which a product complex is formed.

First the direct oxidative insertions (OxIn) of the bare Pd are discussed (all values are enthalpies at 298 K, see Table 5.2). The OxIn of Pd + C$_2$H$_6$ proceeds, via the -7.5 kcal mol$^{-1}$ exothermic formation of the reactant complex $\text{A1a}$, towards a transition state $\text{A1b}$ at 15.4 kcal mol$^{-1}$ relative to the reactants. The overall reaction is exothermic by -11.5 kcal mol$^{-1}$. The product complex $\text{A1c}$ is more stable than the reaction complex by 4 kcal mol$^{-1}$. When substituting one of the hydrogens on ethane by a methyl group, we obtain the OxIn reaction of the slightly more crowded C–C bond in propane. We observe a slight increase in the transition state $\text{A2b}$ by 1.4 kcal mol$^{-1}$, resulting in a barrier of 16.8 kcal mol$^{-1}$. The overall exothermicity drops by 0.7 kcal mol$^{-1}$. Moving on to the OxIn reaction of Pd in the two C$_4$H$_9$ species, methylpropane and butane, we see a similar trend. The transition state again rises by 1.4 kcal mol$^{-1}$, resulting in a barrier of 18.2 kcal mol$^{-1}$ for methylpropane ($\text{A3b}$) and 18.3 kcal mol$^{-1}$ for butane ($\text{A5b}$). It is interesting to see that the insertions into these two bonds, with the same number of methyl substituents, proceed essentially similar. Overall these two reactions behave essentially similar, which is why the remaining discussion will focus on methylpropane only.

Dimethylpropane, which has one carbon atom that is fully substituted by methyl groups, shows a barrier that is 11.5 kcal mol$^{-1}$ higher than that of ethane (transition state complex $\text{A4b}$). This increase in barrier is much higher compared to the less substituted species, in effect comparable to that witnessed for methylpropane C–H activation in chapter 4. The overall reaction is similar in exothermicity; the product is at -10.6 kcal mol$^{-1}$ compared to the reactants. For tetramethylbutane, which is completely substituted by methyl groups, the barrier increases again significantly, to 39.6 kcal mol$^{-1}$, which is 24.2 kcal mol$^{-1}$ larger than for ethane. The reaction becomes more exothermic as the product reaches -19.6 kcal mol$^{-1}$ relative to the reactants.

The increasing barrier for the more methylated bonds is interesting since the trend in reactivity contradicts the trend of bond dissociation energies. The central bond in tetramethylbutane is relatively weak but the barrier for insertion is relatively high. The trends in bond lengths also give interesting insights. The bonds in the substrates become longer as they become weaker and this trend persists for the distance of the ac-
tivated C–C bonds in the transition states, which are 1.945, 1.974, 2.009, 2.102, and 2.340 Å in A1b, A2b, A3b, A4b, and A6b respectively. This corresponds to a stretch of the C–C bond (compared to the substrate) of 0.404, 0.433, 0.465, 0.552, and 0.733 Å, respectively. So we see that the higher transition states correspond to a larger (absolute and relative) stretching of the activated C–C bond in the transition state.

**Table 5.2** Reaction profiles for oxidative insertion OxIn of [Pd] into the R₃C–CR₃ bonds. Shown are 298 K enthalpies (kcal mol⁻¹) relative to reactants. Values in parenthesis include water solvent effects as obtained by the COSMO method.

<table>
<thead>
<tr>
<th>[Pd]</th>
<th>Substrate</th>
<th>a RC</th>
<th>b TS</th>
<th>TS rel. ¹</th>
<th>c P</th>
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<tr>
<td><strong>A Pd</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 H₃C–CH₃</td>
<td>-7.5 (-9.8)</td>
<td>15.4 (12.6)</td>
<td>0.0 (0.0)</td>
<td>-11.5 (-12.7)</td>
<td></td>
</tr>
<tr>
<td>2 H₃C–CH₂Me</td>
<td>-7.6 (-9.9)</td>
<td>16.8 (14.1)</td>
<td>1.4 (1.5)</td>
<td>-10.8 (-14.1)</td>
<td></td>
</tr>
<tr>
<td>3 H₃C–CHMe₂</td>
<td>-6.3 (-7.9)</td>
<td>18.2 (15.7)</td>
<td>2.8 (3.1)</td>
<td>-10.9 (-14.0)</td>
<td></td>
</tr>
<tr>
<td>4 H₃C–CMe₃</td>
<td>-7.4 (-9.1)</td>
<td>26.9 (24.2)</td>
<td>11.5 (11.6)</td>
<td>-10.6 (-14.6)</td>
<td></td>
</tr>
<tr>
<td>5 MeH₂C–CH₂Me</td>
<td>-8.2 (-10.0)</td>
<td>18.3 (15.7)</td>
<td>2.9 (3.1)</td>
<td>-10.1 (-13.0)</td>
<td></td>
</tr>
<tr>
<td>6 Me₃C–CMe₃</td>
<td>-7.6 (-9.0)</td>
<td>39.6 (37.1)</td>
<td>24.2 (24.5)</td>
<td>-19.6 (-20.4)</td>
<td></td>
</tr>
<tr>
<td><strong>B PdCl⁻</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 H₃C–CH₃</td>
<td>-13.1 (-12.5)</td>
<td>12.6 (13.1)</td>
<td>0.0 (0.0)</td>
<td>-12.5 (-7.5)</td>
<td></td>
</tr>
<tr>
<td>2 H₃C–CH₂Me</td>
<td>-13.5 (-12.4)</td>
<td>13.8 (14.7)</td>
<td>1.2 (1.6)</td>
<td>-10.8 (-6.1)</td>
<td></td>
</tr>
<tr>
<td>3 H₃C–CHMe₂</td>
<td>-13.8 (-13.1)</td>
<td>14.5 (16.4)</td>
<td>1.9 (3.3)</td>
<td>-9.2 (-3.4)</td>
<td></td>
</tr>
<tr>
<td>4 H₃C–CMe₃</td>
<td>-14.2 (-12.3)</td>
<td>24.2 (26.9)</td>
<td>11.6 (13.8)</td>
<td>-9.6 (-3.6)</td>
<td></td>
</tr>
<tr>
<td>5 MeH₂C–CH₂Me</td>
<td>-13.9 (-12.4)</td>
<td>15.0 (16.5)</td>
<td>2.4 (3.4)</td>
<td>-8.1 (-2.7)</td>
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<tr>
<td>6 Me₃C–CMe₃</td>
<td>-13.9 (-10.8)</td>
<td>43.3 (46.4)</td>
<td>30.6 (33.3)</td>
<td>-13.9 (-5.9)</td>
<td></td>
</tr>
<tr>
<td><strong>C Pd(PH₃)₂</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 H₃C–CH₃</td>
<td>-1.1 (0.0)</td>
<td>49.1 (50.4)</td>
<td>0.0 (0.0)</td>
<td>25.3 (21.9)</td>
<td></td>
</tr>
<tr>
<td>2 H₃C–CH₂Me</td>
<td>-1.0 (-1.6)</td>
<td>50.5 (51.8)</td>
<td>1.4 (1.4)</td>
<td>28.0 (25.2)</td>
<td></td>
</tr>
<tr>
<td>3 H₃C–CHMe₂</td>
<td>-0.9 (-1.2)</td>
<td>52.5 (54.1)</td>
<td>3.4 (3.7)</td>
<td>29.8 (28.5)</td>
<td></td>
</tr>
<tr>
<td>4 H₃C–CMe₃</td>
<td>-0.9 (-1.9)</td>
<td>60.9 (62.5)</td>
<td>11.8 (12.1)</td>
<td>35.4 (32.8)</td>
<td></td>
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<tr>
<td>5 MeH₂C–CH₂Me</td>
<td>-0.9 (-1.6)</td>
<td>51.9 (53.4)</td>
<td>2.8 (3.0)</td>
<td>29.8 (29.2)</td>
<td></td>
</tr>
<tr>
<td>6 Me₃C–CMe₃</td>
<td>-0.3 (-0.7)</td>
<td>69.5 (72.1)</td>
<td>20.4 (21.7)</td>
<td>41.5 (41.3)</td>
<td></td>
</tr>
</tbody>
</table>

¹ Energies relative to the insertion barrier of ethane.

**Ligand effects:** Adding a Cl⁻ ligand lowers the reaction barrier in most cases. For all substrates except tetramethylbutane, the barrier is lowered by about 3 kcal mol⁻¹. For tetramethylbutane, the barrier becomes higher by 3.7 kcal mol⁻¹. When comparing Pd and PdCl⁻, the change in the barrier height relative to the barrier for ethane is quite small (see also Table 5.2). It is important to stress that the trend in transition state energies is maintained upon addition of Cl⁻. This effect was also seen in chapter 4. However, for the C–H activation the stabilizing effect of the anionic ligand over the whole series was larger because of a more pronounced stabilizing effect on the inherently stronger interaction in that case.
Figure 5.4 Geometries (in Å, deg) of transition states for the OXIn reaction of PdCl– and Pd(PH₃)₂ into the C–C bond of ethane (1), propane (2), methylpropane (3), dimethylpropane (4), butane (5) and tetramethylbutane (6).

Compared to the reactions with bare palladium, barriers for Pd(PH₃)₂ increase by well over 30 kcal mol⁻¹ in all cases. A similar trend in increasing barrier heights is found for the series of substrates as in the reactions with bare palladium. For all Pd(PH₃)₂ insertions the transition state is non-planar, and the catalyst adopts a bent geometry with a P–Pd–P angle of 112 degrees for ethane and most of the bite angles show comparable values. For ethane through butane, the twist angle is about 57 degrees, whereas for dimethylpropane and tetramethylbutane it is 78 and 86 degrees, respectively. Chapter 3 showed how the bite and twist in the transition state geometries are mainly deter-
mined by (Pauli) repulsive effects induced by the phosphine ligands. Larger twist angles and smaller bite angles relieve repulsive interactions but are counteracted by diminishing orbital interactions (larger twist angle) and higher catalyst strain values (smaller bite angle). These same steric effects also explain the larger twist angles for the more highly substituted systems. Compared to chapter 4, with the smaller C–H substrates, we can see that the destabilizing effect is larger in this case, because of the inherently larger steric effects in the more crowded C–C activation.

**Solvent effects:** We have optimized all stationary points with water solvent effects included by the COSMO model. As can be seen in Table 5.2, including solvent effects does not significantly change the trend in activation energies. In case of palladium OxIn, stationary points are all stabilized by a small amount, due to a charge separation that occurs as the palladium binds to the substrate. In the case of PdCl the stationary points are actually destabilized, which can be explained in terms of the high stability of the PdCl as a reactant due to its highly localized charge. For the diphosphine reactions, the transition states become slightly destabilized and the overall exothermicity increases somewhat. Since the COSMO reaction profiles are similar to those in the gas-phase, we will resume our analysis based on the gas-phase results.

### 5.4 Activation strain analysis

The energy profiles $\Delta E(\zeta)$ as obtained from the IRC calculations for the OxIn reactions of the bare palladium into the C–C bonds are shown in Figure 5.5a (we omit butane because it behaves similar to methylpropane). Clearly, the barriers become higher for higher numbers of methyl group substitutions, and the barriers also occur later on the reaction path. In Figure 5.5b, we show the activation strain decomposition, in which the energy is decomposed into the strain energy of the alkane substrate (the upper curves) and the interaction energy between Pd and the substrate (lower curves). Also, in Figure 5.6, a graph of the strain energy is shown, zoomed in to a 0.8 Å stretch of the C–C bond. This gives a clearer view of what happens at the start of the reaction path. For comparison, the energy of stretching the C–C bond in the free substrate and optimizing the structure at each C–C bond length is plotted in Figure 5.6 (lower curves).

Figure 5.5 and Figure 5.6 show that initially the strain energies increase significantly, especially in case of dimethylpropane and tetramethylbutane. Only in the initial 0.1 Å of the reaction path does the strain behave qualitatively different from the simple C–C stretch. After this the curves are relatively similar; the ones of the strain are
shifted upwards by a certain amount due to deformation of the substrate. This increase is mainly due to the fact that the methyl groups have to bend backwards to make the central C–C bond approachable by the Pd. This behavior can be readily observed when visually following the IRC path. This bending of the substituents has been previously observed for the insertion in ethane, where the hydrogens have to bend backwards to make the OxIn reaction possible. It appears, however, that this effect becomes especially pronounced when the carbon bond becomes saturated with methyl groups. This last effect was also observed in the previous chapter.

**Figure 5.5** Activation strain analysis along the reaction coordinate for the oxidative insertion of Pd into the C–C bond of ethane (1, black), propane (2, red), methylpropane (3, yellow), dimethylpropane (4, green), and tetramethylbutane (6, blue): (a) potential energy profiles $\Delta E(\zeta)$, and (b) their decomposition, $\Delta E_{\text{strain}}(\zeta) + \Delta E_{\text{int}}(\zeta)$, upper and lower curve respectively.

We want to demonstrate that the extra methyl groups induce, by their necessity to bend away, a foremost steric effect in the reaction paths. To this end, we construct a series of fictitious transition states with the C–Pd–CH$_3$ moiety of the ethane transition state (C–Pd–C moiety in the case of tetramethylbutane). On this geometry we substitute the R$_3$C moiety as found in the free substrate. These fictitious transition states give us additional insight in palladium’s binding capabilities if the substituents were not allowed to bend away. On these structures, we performed an

**Figure 5.6** The strain (upper curves) along the first 0.8 Å of the reaction coordinate and the energy $\Delta E$ corresponding to a stretch of the C–C bond in the free substrate (lower curves).
analysis including the decomposition of the energy into Pauli repulsion, electrostatic interaction and orbital interaction (see Table 5.3).

Table 5.3 indicates a steric effect if the substituents are not allowed to bend away. In all cases the Pauli repulsion becomes larger in the fictitious transition state, but the increase is especially pronounced for the fully substituted substrates. The energy of the fictitious dimethylpropane transition state is almost 50 kcal mol\(^{-1}\) higher than that of ethane, which is due to large Pauli repulsion. The effect on tetramethylbutane is even more pronounced and the transition state increases by 200 kcal mol\(^{-1}\). Besides the large effect of full substitution, there is also an increase in Pauli repulsion when adding the first two methyl groups. Apparently the added methyl groups also make it somewhat more difficult for the hydrogen that is oriented towards the palladium in the transition state to bend away.

### Table 5.3 Reaction Activation strain analysis of fictitious transition states (see text) of the Pd OxIn reactions. All values are in kcal mol\(^{-1}\).

<table>
<thead>
<tr>
<th>Substrate</th>
<th>(\Delta E^\ddagger)</th>
<th>(\Delta E^\ddagger_{\text{strain}})</th>
<th>(\Delta E^\ddagger_{\text{int}})</th>
<th>(\Delta E^\ddagger_{\text{Pauli}})</th>
<th>(\Delta V^\ddagger_{\text{elstat}})</th>
<th>(\Delta E^\ddagger_{\text{oi}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (\text{H}_3\text{C}–\text{CH}_2\text{Me})</td>
<td>18.3</td>
<td>37.9</td>
<td>-19.6</td>
<td>177.6</td>
<td>-125.3</td>
<td>-71.9</td>
</tr>
<tr>
<td>1 (\text{H}_3\text{C}–\text{CH}_3)</td>
<td>29.6</td>
<td>33.8</td>
<td>-4.2</td>
<td>205.9</td>
<td>-134.5</td>
<td>-75.7</td>
</tr>
<tr>
<td>2 (\text{H}_3\text{C}–\text{CH}_2\text{Me})</td>
<td>30.4</td>
<td>33.3</td>
<td>-2.9</td>
<td>210.7</td>
<td>-138.8</td>
<td>-74.8</td>
</tr>
<tr>
<td>3 (\text{H}_3\text{C}–\text{CHMe}_2)</td>
<td>28.1</td>
<td>31.4</td>
<td>-3.2</td>
<td>211.3</td>
<td>-140.4</td>
<td>-74.1</td>
</tr>
<tr>
<td>4 (\text{H}_3\text{C}–\text{CMe}_3)</td>
<td>60.3</td>
<td>30.2</td>
<td>30.1</td>
<td>317.4</td>
<td>-191.0</td>
<td>-96.3</td>
</tr>
<tr>
<td>6 (\text{Me}_3\text{C}–\text{CMe}_3)</td>
<td>219.6</td>
<td>16.3</td>
<td>203.4</td>
<td>995.9</td>
<td>-548.0</td>
<td>-244.5</td>
</tr>
</tbody>
</table>

\(^a\) Real transition state of the OxIn with ethane.

Returning to the full activation strain analyses, we note that the \(\Delta E(\zeta)_{\text{strain}}\) curves are less steep for the weaker bonds, despite the notable increase at the beginning of the reaction path. In this case, the behavior of the strain curves, after the initial 0.1 Å bond stretch, would indicate a shift of the transition state to the left, at smaller \(\zeta\), contrary to what is observed. However, the \(\Delta E(\zeta)_{\text{int}}\) curves become less stabilizing upon higher substitution numbers and the change is especially pronounced in going to dimethylpropane. Note that the \(\Delta E(\zeta)_{\text{int}}\) curves change even more than the \(\Delta E(\zeta)_{\text{strain}}\) curves and are dominant in determining the position of the barrier. This behavior is especially pronounced for the more highly substituted dimethylpropane and tetramethylbutane. For tetramethylbutane the interaction weakens significantly; the interaction curve is even positive along part of the reaction path. The weakening in interaction energy is also observed for the smaller differences between ethane, propane and methylpropane.
With the energy decomposition (detailed analysis not shown here) it becomes clear that especially the orbital interactions $\Delta E_{oi}$ are important, compared to the combined influence of $\Delta V_{elst}^*$ and $\Delta E_{Pauli}$. The orbital interactions are, along the reaction coordinate, the most stabilizing for the interaction of Pd with C$_2$H$_6$. To understand more about the nature of these orbital interactions, we have looked at overlaps between HOMO and LUMO orbitals on catalyst and substrate, and orbital energies and populations of these HOMOs and LUMOs. An analysis of these plots tells us that an important effect lies in the back-bonding from the Pd 4$d$ to the C–C $\sigma^*$ bond. This aspect can be mainly traced back to the energy of the C–C $\sigma^*$ orbital during the reaction, which is notably higher for the substituted substrates (see also Figure 5.7a). Also the steepness of the LUMO energy curve diminishes, which is in correspondence with the behavior of the interaction energy.

Another effect to be taken into account when explaining the diminishing interaction energy is a geometrical effect induced by the reluctance of the substituents to bend away and make room for the approaching palladium. The effect of this is that, along the reaction coordinate, the palladium is further away from the C–C bond when the number of methyl groups increases (see Figure 5.7b), leading to a less attractive interaction energy at that point. This is another good example of the necessity of taking into account the geometrical relaxation effects, see section 2.5. In order to get a clearer picture of this effect, we again performed an analysis on fictional transition states. By keeping the C–Pd–C central part fixed in the geometry of the ethane OxIn transition state (the rest of the system is optimized), we can add the methyl groups.

Figure 5.7 (a) Energies of the C–C* LUMO orbital and (b) distance of Pd measured perpendicular to the C–C bond along the reaction coordinate for the oxidative insertion of Pd into the central C–C bond of ethane (1), propane (2), methylpropane (3), dimethylpropane (4), and tetramethylbutane (6).
without changing the actual distance of palladium to the C–C bond. The analyses of these points are found in Table 5.4.

Table 5.4 Activation strain analysis (see computational details) of fictitious transition states (see text) of the Pd OxIn reactions. All values are in kcal mol$^{-1}$.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta E^\ddagger$</th>
<th>$\Delta E^{\ddagger\text{strain}}$</th>
<th>$\Delta E^{\ddagger\text{int}}$</th>
<th>$\Delta E^{\ddagger\text{Pauli}}$</th>
<th>$\Delta V^{\ddagger\text{elstat}}$</th>
<th>$\Delta E^{\ddagger\text{elstat}}$</th>
</tr>
</thead>
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<td>-19.6</td>
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<tr>
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<td>-14.2</td>
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<td>-71.5</td>
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<tr>
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<td>197.5</td>
<td>-131.1</td>
<td>-69.9</td>
</tr>
<tr>
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<td>41.4</td>
<td>10.2</td>
<td>316.4</td>
<td>-199.5</td>
<td>-106.7</td>
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We want to understand with this analysis why the palladium becomes further distanced from the C–C bond as the number of methyl groups increases. We can see from the fictional transition states analyses that, if we would place the palladium closer to the C–C bond, this results mostly in an increase in the Pauli repulsion term. The palladium is “pushed away” by steric effects. This can be rationalized by the fact that it will become increasingly difficult for the substrate to bend away and make room for the palladium to approach the central bond. Again, this effect is most pronounced for the fully substituted substrates, but it is also a factor to be taken into account when adding the first of the methyl groups.

In general, we can conclude that there is a definite pronounced steric effect upon adding the methyl groups due to the necessity of the substituents (methyl groups but also hydrogens) to bend away. For the highly substituted systems, this behavior is especially pronounced and is expressed at the beginning of the reaction path as a sharp initial increase in strain energy. However, the overall strain energy curves indicate a lower (and earlier) barrier for higher substitution, while the actual trend is the opposite. The explanation for the trends in barrier heights lies in the behavior of the interaction energy curves, which become weaker and less steep upon higher methyl substitution. This induces a higher barrier that lies further along the C–C stretch reaction coordinate. This decrease of interaction can be attributed to two effects: 1) a decrease of back-donation from the metal to the C–C $\sigma^*$ bond, due to an increasingly higher LUMO energy; 2) the increasing difficulty of bending away the substrate substituents makes it more difficult for the palladium to approach the C–C bond.

Ligand effects: In Figure 5.8a the energy profiles can be found for the OxIn reaction of ethane with the three different catalysts: Pd, PdCl$^-$, and Pd(PH$_3$)$_2$. In Figure 5.8b, we show the extended activation strain analysis of the interaction of ethane with these catalysts.
As mentioned previously, the addition of a Cl ligand to Pd reduces the barrier of C–C insertion (see also chapter 4). Besides reducing the height of the barrier, it is also shifted more to the reactant side where the C–C distance is shorter. In Figure 5.8b it is clearly seen that the strain curve for Pd and PdCl– are practically identical. The reason is that PdCl– is hardly deformed during the reaction; and the trends in the total strain energy is due to trends in the strain energy of the substrate, which behaves similar along the reaction coordinate. Thus, to understand the differences between the reaction profiles of Pd and PdCl– we can focus on $\Delta E_{\text{int}}$. The PdCl– catalyst induces a stronger interaction with the C–C bond. The result is not only that $\Delta E_{\text{int}}$ is more negative, thus decreasing the barrier, but it also has a more negative slope, resulting in an earlier barrier along $\zeta$.

The diphosphine palladium catalyst induces a substantially higher reaction barrier compared to bare palladium. Furthermore, the barriers are shifted to the right along the reaction coordinate; the transition state occurs at a larger C–C distance. Figure 5.8b shows that at small values for $\zeta$, there is a sharp increase in strain energy. As we know, this is caused by the necessity of the two ligands to bend away from their intrinsic linear geometry. Interesting is the analogy with the need for the methyl groups to bend away in order to form a complex with the catalyst. In both case the strain energies rise quickly at the start of the energy profile. Similar to the substituents on the substrates, the phosphine ligands induce a steric hindrance due to which it is more difficult for the palladium center to reach the bond. Accordingly, the distance of palladium to the C–C bond at the transition state becomes larger when the ligands are introduced, and the interaction becomes less stabilizing. This effect becomes stronger...
as the substrate becomes more bulky, see also Figure 5.3 and Figure 5.4, which makes sense when taking into the account the steric nature of the ligand effects.

5.5 Conclusions

Upon increased substitution with methyl groups of the alkane C–C bond the barrier of oxidative insertion activation increases. This is in contrast to the observation that the activated bonds become weaker along this series. One aspect of the increase in barrier is due to a less favorable back-bonding from the palladium to the substrate, combined with increasing steric destabilization. The decrease in back-bonding can be attributed to the energy of the $\sigma^*$ orbital of the C–C bonds, which decreases less along the reaction coordinate for the more substituted bonds. The second effect is the increasing difficulty for palladium to approach the C–C bond. This is caused by steric repulsion, which increases because the increasing number of methyl groups are more difficult to bend away to make room for the palladium. This effect is especially pronounced for the fully substituted bonds.

PdCl\textsuperscript{−} insertions proceed more easily compared to Pd, because of the more favorable interaction of PdCl\textsuperscript{−} with the C–C bond, due to a smaller Pauli repulsion. For Pd(PH\textsubscript{3})\textsubscript{2} insertions, however, the barriers of insertion increase significantly compared to the Pd and PdCl\textsuperscript{−} insertions. The catalyst needs to deform before the reaction can proceed, which results in a larger strain energy. Another important factor is a decrease in interaction energy because of larger Pauli repulsion induced by the ligands. It is interesting to compare the results with those of the bulky C–H activations in the previous chapter. It is clear that the effects on the interaction energy have a greater impact on the C–H insertion (where the PdCl\textsuperscript{−} is more stabilizing compared to C–C), and that steric effects have a larger impact on the C–C insertions, where the Pd(PH\textsubscript{3})\textsubscript{2} has a larger destabilizing effect. These type of mechanisms had already been alluded to in the analysis of the various ligand effects in chapter 3.